アフリカの半乾燥地域における環境変動と人間活動に関する研究

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平成17年3月

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はしがき

最終氷期以降、気温や降水量、海流、風系の変化は、アフリカの環境を複雑に変化させ、乾燥地域も拡大・縮小を繰り返した。近年になると、地球温暖化が問題になり、アフリカにおいても降水量減少や植生破壊による「砂漠化」など深刻な問題が生じている。特に、アフリカの場合、人口急増による人為的影響（農地・放牧地の拡大による植生破壊、薪の使用量増大による森林破壊、放牧地の拡大による土壌劣化など）も加わって土地を荒廃させ、乾燥地域を拡大させた。アフリカはそのほとんどの国が農業を主たる生業としているため、気候変動は人々の生活に直接大きな影響を及ぼすことになる。アフリカに大きく広がる半乾燥地域では、その厳しい気候環境ゆえ、わずかな気候変化が環境要因の複合的な相互作用によって大きな環境変化として現れる。本研究ではアフリカの半乾燥地域における近年の環境変動の動態を明らかにし、近年の環境変化とその人々に及ぼす影響やそれに対する住民の対応策を探ることを目的としている。したがって、まず、アフリカのナミビアおよびその周辺国の半乾燥地域において、最終氷期以降の古環境を復元し、完新世の環境変化を解明した。さらに、近年の降水量変化や乾燥地域の空間的広がり、植生・土壌の変化、土地利用や農業の変化を明らかにした。そして、両者の研究結果をもとに、将来にわたってアフリカの環境を予測し、今後の対策を検討する。そのために、地形学、第四紀学、気候学、土壌学、植生地理学、植物生態学、熱帯農学など多角的に調査を実施した。

平成17年3月
水野一晴

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研 究 成 果

PREFACE

From 2001 to 2004, research was carried out in Namibia, under a Grant-in-Aid of Scientific Research (Project No. 13371013 headed by Dr. Kazuharu Mizuno, Kyoto University) from the Ministry of Education, Science, Sports, Culture, and Technology of Japan. This supplemental issue presents the results of this research project.

Since the Last Glacial Stage, changes in temperature, precipitation, ocean currents, and wind systems have had complicated effects on the environment of Africa, where the dry regions have expanded and contracted repeatedly. In recent years, global warming has become a major factor, and this situation has been further complicated by desertification following a decrease in precipitation and the destruction of vegetation. An upsurge in human activities resulting from the rapid increase in population, such as the expansion of farmland and grazing land leading to soil degradation, and deforestation owing to excessive collection of firewood, have contributed to desertification. Environmental changes have a great influence on people's lives in this region, given that agriculture is the main form of employment in most African countries.

In the severe environments of semi-arid areas, even a slight change in the environment can produce relatively large changes overall. Environmental changes lead to a chain reaction, which is amplified by synergistic effects that affect a wider area through the general circulation of the atmosphere. Therefore, it is extremely important to grasp the dynamic relationships between the natural environment and human activities, not only locally, but globally.

This research project sought to determine the environmental history of the semi-arid area of Namibia from the Last Glacial Stage, and recent environmental changes, including changes in climate, topography, vegetation, soil, land utilization, and agriculture. The project involved interdisciplinary cooperation with experts in geomorphology, Quaternary research, climatology, phytogeography, pedology, plant ecology, and tropical agriculture, an approach that is very important for a project like ours.

In the semi-arid regions of Africa, the effects of climatic changes on the local environment and ecosystems remain unclear. Subtle changes in climate, topography, vegetation, soil, and wild animal populations, as a result of human activities, can have a great effect. It is anticipated that our research will stimulate further study of natural environments in Africa.

K. Mizuno

VEGETATION SUCCESSION AND PLANT USE IN RELATION TO ENVIRONMENTAL CHANGES ALONG THE KUISEB RIVER IN THE NAMIB DESERT

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ABSTRACT The aim of this study was to clarify the relationship between environmental change and vegetational succession in the Kuiseb River area of the Namib Desert. The results reveal the following: 1. About 5000–7000 years ago, wetter conditions prevailed in the Kuiseb River basin, forming a wider riverbed than at present. 2. About 600 years ago, a low terrace formed. The low terrace was characterized by the growth of acacia trees and other vegetation, which trapped and accreted aeolian sand. 3. About 400 years ago, the trapped and accumulated sand began to form a sand dune, eventually killing the tree population. 4. At the present time, all of the buried acacia trees have died and have been replaced by salvadora bushes, which continue to trap sand and increase the size of the dune. 5. Plants such as *Acacia erioloba*, *Faidherbia albida*, and *Acanthosicyos horridus* are very important food sources and shade plants for the local Topnaar people and their livestock. The succession of vegetation in response to environmental change has a profound impact on life in the Kuiseb River area, owing to the harsh environmental conditions and scarce plant life in the region.

Key Words: Environmental change; Sand dune; Vegetation succession; Kuiseb River; Topnaar people.

INTRODUCTION

Desertification has been identified as a major problem in Africa in recent years. Natural environmental changes and human activities have contributed to this desertification. For instance, population increase lead to the widespread destruction of vegetation and/or excessive pasturage. Irregular movement of the Intertropical Convergence Zone (ITCZ) causes droughts.

Environmental change is also a problem in Namibia. Average temperatures in Windhoek increased by about 0.0023°C per year from 1950 to 2000 (Ministry of Environment and Tourism, Republic of Namibia, 2002). Although the average annual precipitation recorded by meteorological stations in Namibia was 272 mm from 1915 to 1997, annual precipitation exceeded this rate in only two out of sixteen years from 1981 to 1996. Because rising temperatures increase evaporation rates, the region becomes progressively drier, even while experiencing steady rates of precipitation.

Most of the rivers in Namibia are seasonal in nature, flowing only after periods of intense rainfall. The only non-seasonal rivers in Namibia are the

Orange River in the south, and the Kunene, Kavango, Kwando-Linyanti-Chobe, and Zambezi rivers in the north. The Kuiseb River defines the border between the stony desert and the sand desert, and precipitation in the upper stream area ranges from 200 mm to less than 20 mm annually; in addition, most of this surface water is absorbed by the sandy river bed. The middle and lower areas of the Kuiseb River usually remain arid, except during occasional periods of flooding. The trees on the riverside of the Kuiseb River have partially died, for a variety of reasons. The objective of this paper was to clarify the relationship between desertification, vegetational succession, and human activity.

STUDY AREAS AND METHODS

I. Study Area

The Namib Desert borders the Atlantic Ocean on the west coast of Namibia. Although the age of the Namib Desert has long been a topic of controversy, most agree that the climate of the narrow coastal track between the southern Atlantic Ocean and the Great Western Escarpment has varied from arid to semi-arid for at least the last 80 million years (Seely, 1992). The annual precipitation in the Namib Desert is less than 50 mm. The average rainfall varies from less than 15 mm per year on the coast to about 100 mm per year in the eastern desert. The dominant southwesterly winds carry cool air from the Benguela Current inland, creating a cool inversion layer, i.e., a layer of cooler air underlying a warmer layer. This inversion layer minimizes turbulence in the atmosphere, impeding cloud development and rain formation (Seely, 1992).

This study was performed in the Gobabeb region of the Kuiseb River during August and November of 2001 and February of 2002 (Fig. 1, 2). Although the annual rainfall in Gobabeb is only 27 mm (Fig. 3), precipitation derived from fog is 31 mm (Fig. 4, 5) (Lancaster *et al.*, 1984). The fog, which can travel tens of kilometers inland on many mornings, is densest at elevations of between

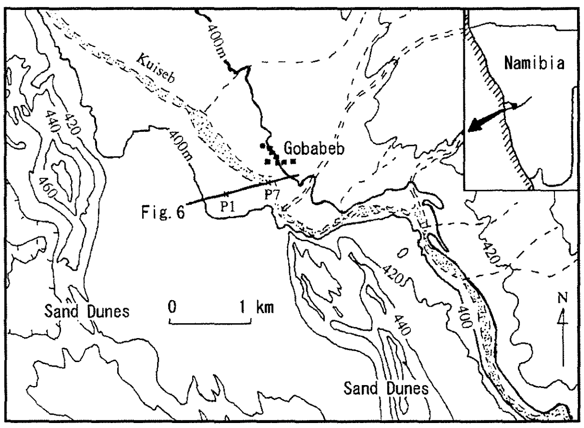


Fig. 1. Study area.
P1, P7: Soil profile (Fig. 14).

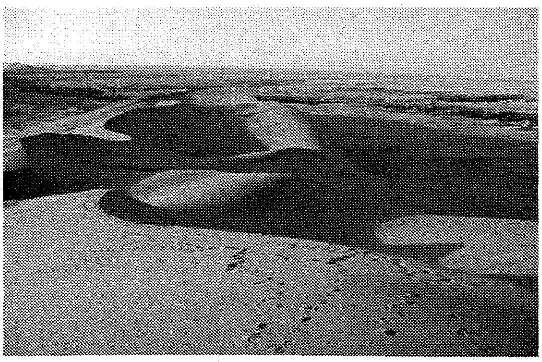


Fig. 2. Sand dune and the Kuiseb River near Gobabeb.

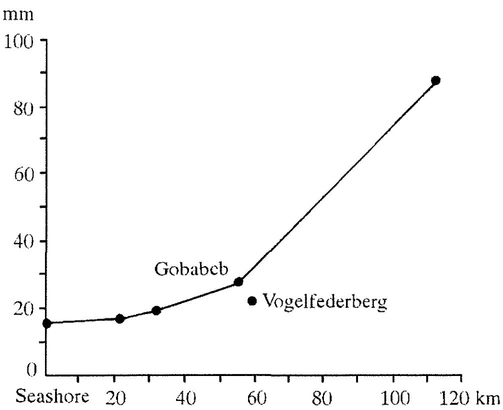


Fig. 3. Mean annual rainfall in the central Namib Desert plotted against distance from the coast (Lancaster *et al.*, 1984).

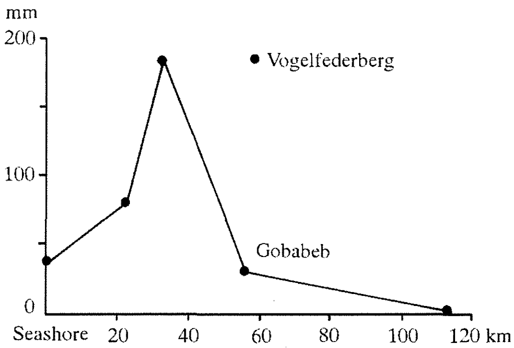


Fig. 4. Mean annual fog water precipitation in the central Namib Desert plotted against distance from the coast (Lancaster *et al.*, 1984).

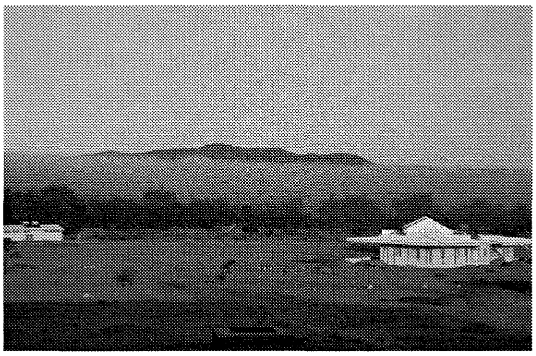


Fig. 5. Fog in the morning at Gobabeb.

300 m and 600 m. Fog-water precipitation is greatest at about 40 km inland from the coast because of the gradual increase in altitude of the Namib Desert, from the coast to inland. Because fog-water condenses on inselbergs such as Vogelfederberg, the inselbergs can support plant life in the desert. The fog in Gobabeb formed and spread on an average of 37 days per year from 1976 to 1981. Fog is an important source of water for animals and plants in the Namib Desert (Lancaster *et al.*, 1984).

II. Methods

A belt transect of 1000 m in length was taken across the Kuiseb River. The topographic profile was obtained by measuring along the transect. Vegetation and soil profiles were investigated along the transect. A pit of 1–2 m in depth was used for a soil survey and the soil profile was analyzed. The depth of the water table was measured in the well.

Soil water was measured in water content by volume using a Hydro-sense soil moisture meter made by Campbell Scientific Ltd. Radiocarbon (^{14}C) dating was measured by Beta Analytic Inc., in Florida. Samples 3 and 4 for dating were identified as *Acacia erioloba* and *Faidherbia albida* based on thorn morphology. Branch tips of dead trees were collected for dating samples, and were assumed to represent the site of most recent growth. Radiocarbon dates are shown as conventional ^{14}C ages.

RESULTS AND DISCUSSION

I. Environmental Change and Vegetational Succession

Figure 6 shows the topographic profile along the transect. Three terraces were classified, at altitudes of about 0 m, 2 m, and over 10 m from a base level (Fig. 6). The terrace at 0 m altitude is referred to as the low terrace; the middle terrace was at 2 m, and the high terrace was at over 10 m.

Calcretes formed on the middle terrace (Fig. 7). Calcretes are encrustations of salt where $CaCO_3$ has accumulated through the evaporation of soil water. These calcretes were dated to about 5300 ± 60 years BP and 6740 ± 50 years BP using ^{14}C dating (sample numbers 1, 2; Table 1). Because the calcretes are thought to have formed through the evaporation of water raised via capillary pressure from the shallow water table, the middle terrace covered by the calcrete was probably the riverbed 5000–7000 years ago. Rounded gravel is common on the land surface, and provides further evidence of the location of the former riverbed. In the period when the calcretes were made, the water table probably rose owing to much rain. In Africa, the warm period of the early Holocene (9000–8000 years ago) and the hot period of the middle Holocene (7000–5000 years ago) were both very wet periods during which much rain fell inland of the Sahara Desert. It is thought that the present desert was extensively covered by vegetation typical of a savanna or steppe, because of the rainfall at that time, and that many lakes, such as Lake Chad, extended into the desert (Kadomura, 1992). The period when middle terrace had the higher water table coincides with the wet time in the other area.

The water table underlying the forest of the low terrace is shallow, at a depth of about 13 m. The forest itself is mainly populated by tall trees such as *Faidherbia albida* (acacia), *Tamarix usuneoide*, and *Euclea pseudebenus*.

The sand dunes on the west side of the riverbed are located on the border between the low terrace and the middle terrace. Sand is carried by the southwest wind perpendicular to the river, and accumulates in the forest on the west side of the river. This process is probably the

Fig. 7. Calcrete ($CaCO_3$) in the middle terrace.

Table 1. ^{14}C dates of samples (conventional ^{14}C ages).

Sample number	Material	^{14}C data (yr BP)	$\delta\ ^{13}C$ (permil)	Laboratory code number (Beta-)
1	Carbonate	5300±60	−6.2	164939
2	Carbonate	6740±50	−7.2	176921
3	Wood	300±60	−23.8	165889
4	Wood	550±50	−23.9	165888

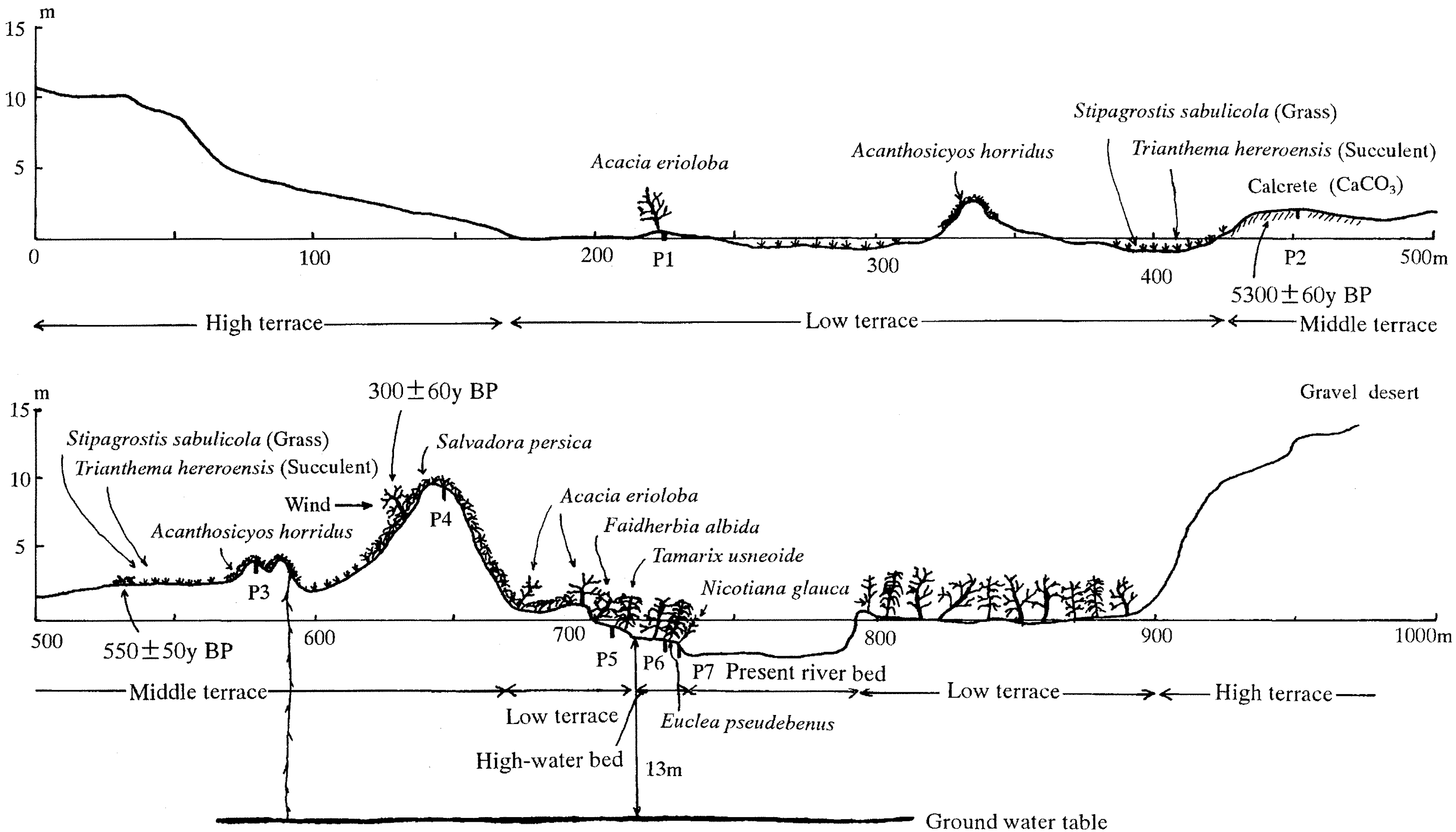


Fig. 6. Topographic profile and vegetation along transect (Fig.1).
P1-P7: Soil profile (Fig.14).

mechanism responsible for the formation of the 10 meter high sand dune that is seen today (Fig. 8), based on the observed depth of tree burial in this area. The movement of the sand dune has been recorded as northern to northeastern, and the rate of movement ranges from 30 to 180 cm per year in Gobabeb (Ward & Brunn, 1985).

On November 29, 2002, a pole was erected on the edge of the sand dune to monitor the movement of the dune. On March 1, 2003, the pole was not buried at all and no sand dune movement was observed. By August 10, 2003, the pole was buried to a depth of 60 cm and the sand dune had advanced 100 cm horizontally. By November 30, 2003, the pole was buried to a depth of 70 cm and the sand dune had advanced 145 cm from its initial position. By August 5, 2004, the pole was buried to a depth of 130 cm and the sand dune had advanced 220 cm from its initial position. Therefore, it was concluded that the sand had advanced discontinuously, and that its rate of advance was 120–145 cm/year (November 2002–August 2004).

Acacia trees (*Acacia erioloba*, *Faidherbia* (*Acacia*) *albida*) on the middle terrace are buried in the sand (Figs. 6 & 9). Radiocarbon dating (^{14}C) of one buried acacia tree established an age of death at about 300 ± 60 years BP (sample 3, Table 1). Therefore, it is considered that the low terrace has been formed 500–600 years ago and formation of the sand dune may have begun approxi-

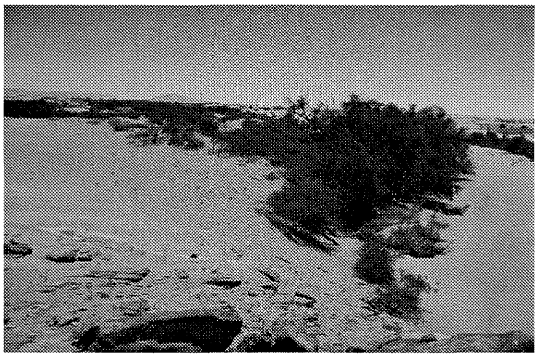


Fig. 8. Flying sand captured by trees along the Kuiseb River and acacia trees covered with sand.

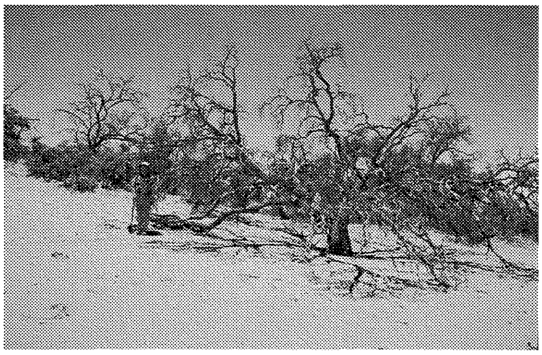


Fig. 9. Growth of the sand dune and dead acacia trees.

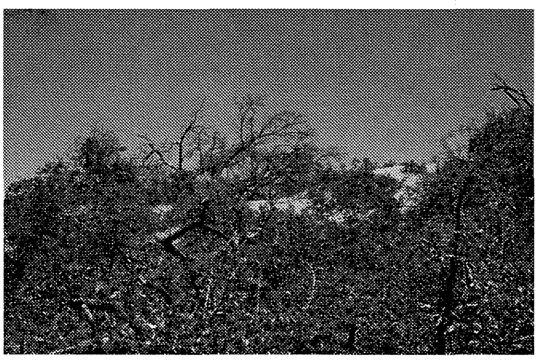


Fig. 10. *Salvadora persica* covering the sand dune.

Fig. 11. Soil profile of plot covered by *Salvadora persica*.

mately 400 years ago. Although the exact cause of death remains unclear, it is likely that the oxygen supply to the roots decreased, and the nutritional resources in the soil became depleted. These points will be examined further in a later discussion.

In sand dunes covered by salvadora bushes (*Salvadora persica*), the trunks of salvadora bushes extend deep into the ground (Figs. 10 & 11). The bushes capture the moving sand and this contributes to the expansion of the sand dune.

The most important plant for the people of the Kuiseb River is !nara (*Acanthosicyos horridus*) (The symbol ! denotes clicks in the Nama language.). The low and middle terraces of the study area are dotted with !nara bushes of 1 m to 3 m in height (Fig. 12). The roots of the !nara plant sometimes extend more than 15 m underground, which is the approximate depth of the water table in this region, in order to reach the water supply.

Based on the soil profile, it seems that the !nara plant extends its trunk upward to escape the smothering sand (Fig. 13). Although the low and middle terraces are covered with !nara, the high terrace and sand dune are not, perhaps owing to the varying availability of groundwater. The sand dune currently dominated by salvadora growth is thought to have previously supported !nara growth but, because the groundwater supply became unreachable for the !nara plant, this population has declined.

Although two similar mounds are located on the middle terrace, one is covered with !nara and the other is characterized by fragments of carbonizing acacia trees. Acacia trees are thought to have been distributed extensively during the wet period when the middle terrace was the high-water bed of the river, but they did not survive the dry period after it. Radiocarbon dating (^{14}C) sets the date of this die-off period at about 550 ± 50 years BP (sample 4, Table 1). It is possible that acacia trees were still widely distributed as recently as about

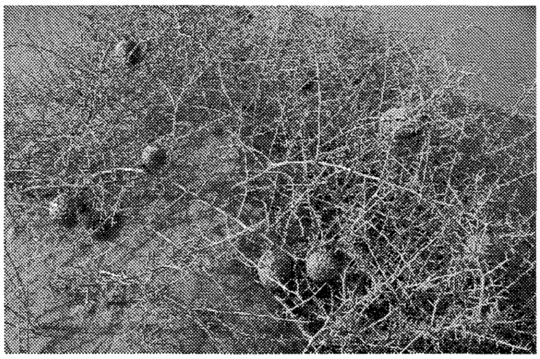


Fig. 12. !Nara bush (*Acanthosicyos horridus*).

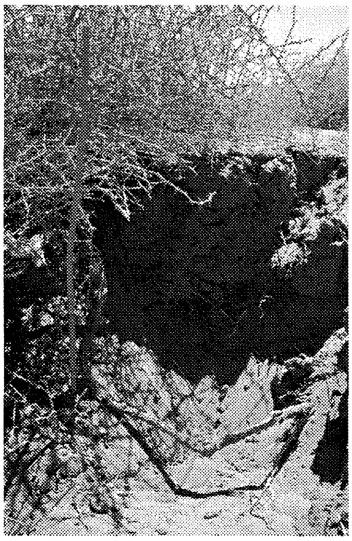
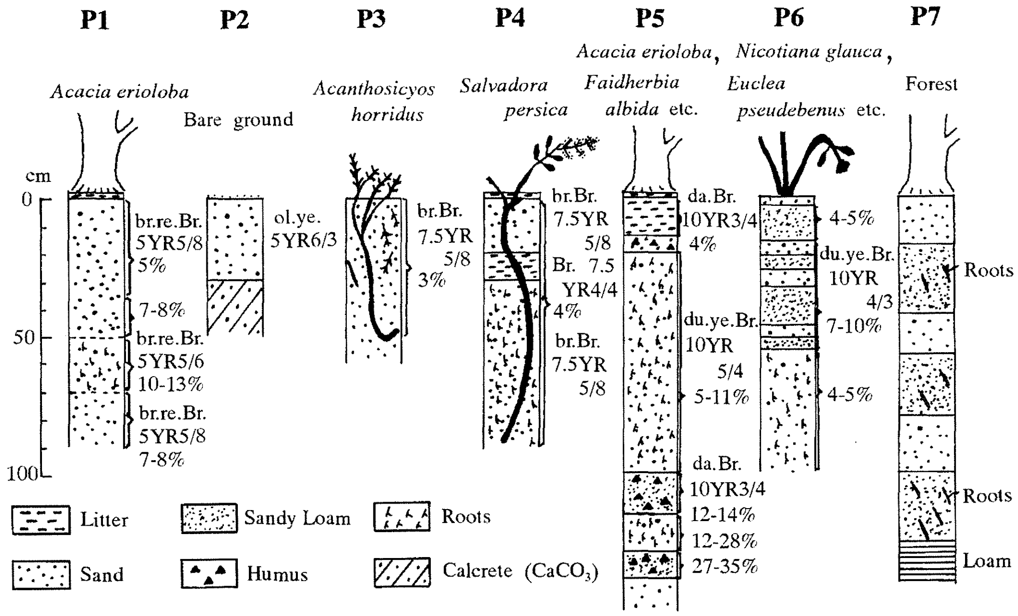


Fig. 13. Soil profile of plot covered by !nara (*Acanthosicyos horridus*).



Br.: brown br.Br.: bright brown br.re.Br.: bright reddish brown

da.Br.: dark brown du.ye.Br.: dull yellowish brown ol.ye.: olive yellow

3%: water content by volume

Fig. 14. Soil profile of plots shown in Fig. 6.
5YR5/8: Soil color.

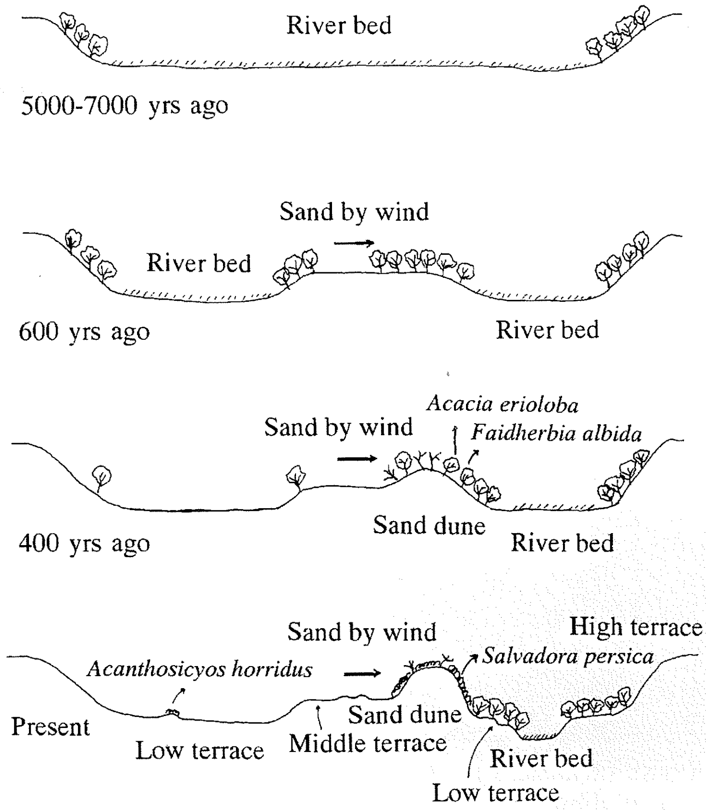


Fig. 15. Environmental change and vegetational succession in the study area.

600 years ago.

The low terrace is characterized by either bare land or grasses such as *Stipagrostis sabulicola* and the succulent dwarf tree *Trianthema hereroensis*. *Stipagrostis sabulicola* has a root system that can reach from 1 to 10 cm in depth and 20 m in width; it absorbs fogwater efficiently. *Trianthema hereroensis* absorbs fog-water directly through the leaves and stems (Seely *et al*., 1998).

The sandy soil that supports both !nara (P3) and salvadora (P4) has a water content by volume of only about 3 to 4% (Fig. 14). The scarcity of soil water content is another factor that encourages the roots of !nara to reach 15 m or more in depth.

Salvadora can absorb a great deal of water through its densely packed fine roots that range in length from 20 cm to more than 1 m. Although the litter 10 cm in thickness occur at depths of between 20 and 30 cm, this may record a time when sand movement was more moderate than at present. Recently, the rate of sand movement appears to have increased.

The sandy soil in the acacia-dominated forest on the low terrace (P5) has a water content by volume of 4 to 10% up to a depth of 100 cm. In depths of 100 cm to 150 cm, the sandy loam soil mixed with humus has a 12 to 35% water content by volume. Similarly, the soil from 50 cm to 70 cm depths of P1 has a water content of 10–13% by volume. The forest soil with diverse vegetation populations (P7) has deeper, finer roots. The soil of the high-water bed, which overlies trees such as *Nicotiana* and *Euclea* (P6) has similarly deep, fine roots.

The above-mentioned phenomena is summarized as Figure 15:

1. From 5000 to 7000 years ago, relatively wet conditions led to the formation of a wider riverbed than that of the present.
2. About 600 years ago, the low terrace formed. The low terrace was characterized by the growth of acacia trees and others, which trapped and accreted sand.
3. About 400 years ago, the sand dune began to form from trapped and accumulated sand, eventually killing the tree population.
4. At the present time, all acacia trees in the sand dune have died and have been replaced by salvadora bushes, which continue to trap sand and increase the size of the dune. The low terrace near the present riverbed is covered by a forest of *Acacia erioloba*, *Faidherbia* (*Acacia*) *albida*, and *Tamarix usuneoide*. The high-water bed along the riverbed is occupied by *Euclea pseudebenus* and *Nicotiana glauca*. The low terrace far from the riverbed is bare ground, dotted with some grass. !Nara partially grows on the low and middle terraces far from the riverbed.

II. Significance of vegetation for people living near the Kuiseb River

The pastoral Topnaar people are part of the Nama people of Khoi Khoi in Khoisan, and live along the Kuiseb River. The most important source of food for the Topnaar is !nara, or *Acanthoicyos horridu*s. An alternative name for the

Topnaar is *!naranin,* and is derived from the word !nara, illustrating the centrality of this plant to the culture (Dentlinger, 1977; Van den Eynden *et al.*, 1992).

!Nara fruits are eaten fresh and are almost the only food available during the harvest season (Ito, 2003). The fleshy portion of the ripe fruit is boiled in a drum and mixed with mealie meal to make a sweet porridge (Wyk & Gericke, 2000).

Like the watermelon, which originated in the Kalahari Desert, !nara thrives in an arid climate, accessing deep groundwater and retaining water in the fruit of the plant. !Nara seeds are sold for food or oil in the city, and are an important source of income for the Topnaar people (Ito, 2003).

!Nara grows widely in the !nara fields near the lower reaches of the Kuiseb River. Although the Topnaar people harvest wild !nara from December to March and rely on !nara as their most important source of food and income, the amount of !nara grown in this area has dramatically declined in recent years because of a lack of flood water, following a construction of a dam. Flood water is considered to be vital to the regeneration and survival of !nara.

Acacia erioloba (camel thorn) is a tall tree that grows in the driest regions of the Kuiseb River, and is one of the most important sources of firewood in southern Africa. An infusion of camel thorn gum is taken for coughs, colds, and tuberculosis, and a bark decoction is taken for diarrhea. A root decoction is taken for coughs and nosebleeds (Wyk & Gericke, 2000). In times of famine, the Topnaar people eat the pulp of the pods. The roasted seeds are sometimes

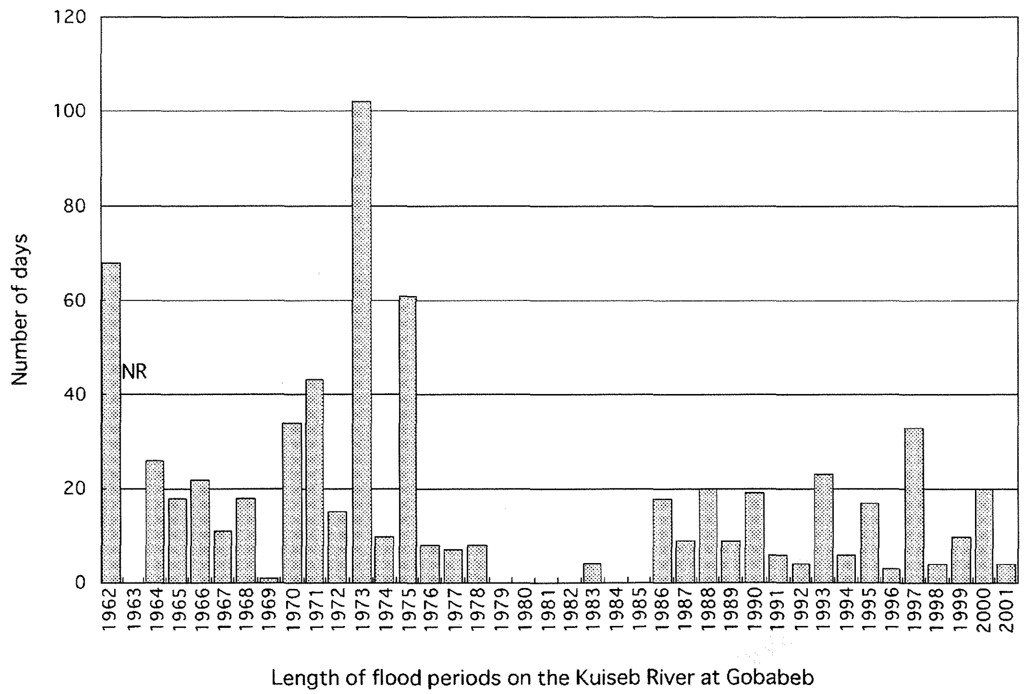


Fig. 16. Summary of Kuiseb River flooding at Gobabeb, 1962–2001.
1962–1984: Seely *et al.*, 1981; Ward & Brunn, 1985. 1985–2001: from data of the Desert Research Foundation of Namibia.

used as a coffee substitute (Van den Eynden *et al.*, 1992). One of the greatest benefits offered by the camel thorn is the shade and shelter it provides in the desert for humans and livestock (Craven & Marais, 1986). In addition, *Acacia erioloba* is an important tree for the Topnaar people because their goats eat the pods and leaves.

Goats also use the tree *Faidherbia albida* as a food source. In contrast to other trees, *Faidherbia albida* sheds its leaves at the onset of the rainy season and remains leafless until the beginning of the dry season (Craven & Marais, 1986). Thus, its leaves and pods become the most important food source for goats during a season of short supply.

Although flooding of the Kuiseb River has been recorded in Gobabeb every year from 1962 to 2001 (Seely *et al.*, 1981; Ward & Brunn, 1985; data of the Desert Research Foundation of Namibia), very little water flowed during the summers of 1979 to 1985 because of dryer conditions (Fig. 16). If aridity continues to increase, the tree population will suffer, and so will the people.

CONCLUSIONS

Environmental changes along the Kuiseb River, including changes in topography, vegetation, and soil, vary according to climatic fluctuations. It is vital, for the survival of the Topnaar people, that we better understand the relationship between environmental change and human activity.

The Topnaar people use the native vegetation in different ways. Because vegetation is very sparse along the Kuiseb River, it is very precious. Acacia trees have been buried and died, owing to expansion of sand dunes; they have been replaced by salvadora bushes capable of adapting to the changing conditions. !Nara has also disappeared as a result of environmental change. People's lives have been greatly affected by these changes in vegetation.

A slight change in temperature has strongly influenced the distribution of vegetation in the severely cold climate of the African high mountains (Mizuno, 1998, 1999, 2000, 2001, 2005; Mizuno & Nakamura, 1999). Similarly, in the severely dry environments of the desert, a slight change in precipitation produces a striking change in vegetation. The chain reaction of environmental change becomes a positive feedback loop, and the effects continue to increase. It is vital, therefore, that we investigate and understand the dynamic relationship between environment and vegetation, not only for the Topnaar people, but for all people.

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LANDFORM DEVELOPMENT ALONG THE MIDDLE COURSE OF THE KUISEB RIVER IN THE NAMIB DESERT, NAMIBIA

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ABSTRACT The hyperarid to arid Namib Desert extends along the west coast of southern Africa. The Kuiseb River is one of the major ephemeral rivers originating in the interior highland, and crosses the Namib Desert. Fluvial terraces are well developed along the middle reaches of the Kuiseb River near Gobabeb, and are classified into four surfaces: upper (H), middle 1 (M1), middle 2 (M2), and lower (L). Layers of calcrete are founded on the M1 and M2 surfaces, and gypcrete layers are founded on the H surface. Dead tree matter, buried by dune sand on the L surface, dates to 300±60 years BP and 550±50 years BP. The calcareous crusts on the M1 surface date to 5,300±60 years BP and 6,450±50 years BP, and those of the M2 surface date to 22,070±260 years BP. The presence of calcrete suggests that the ground water level was higher when the M1 and M2 surfaces were formed than it is at the present time. Tree size distribution on the L surface demonstrates that the L surface was also formed during a relatively wet period. It may be concluded, therefore, that these fluvial terraces record the humid periods of ca 22 ka, 5–6.5 ka, and 300–600 years BP in the catchment area of the Kuiseb River. The presence of a water-soluble gypsum crust on the H surface suggests that the paleohydrologic environment of these terrace-forming periods probably involved increased rainfall in the interior highland east of the desert.

Key Words: Namib Desert; Kuiseb River; Ephemeral River; Fluvial Terrace; Calcrete, Dendrochronology; Paleohydrology.

INTRODUCTION

The Namib Desert stretches along the Atlantic coast of southern Africa, measuring about 1,400 km in length and varying between 40 and 120 km in width. The Namib Desert is one of the driest deserts in the world. The cold Benguela current that flows northward along the coast of Namibia strongly influences the extremely dry climate of the Namib Desert. The whole area of the Namib Desert receives less than 200 mm precipitation per year.

Previous studies have shown that marked environmental changes occurred in the African continent during the Quaternary age. However, current understanding of paleoenvironmental change in southern Africa remains insufficient, and the area understudied, as compared to parts of northern Africa centered on the Sahara Desert. Paleoenvironment evidence in dry regions is rarely well-preserved.

Ephemeral rivers are the areas of particular interest in which the paleoenvironmental record of the desert has been well preserved. The fluvial sequences in the Namib Desert indicate alternating periods of aggradation and degradation throughout the Quaternary (Heine, 1998; Lancaster, 2002). Late Pleistocene and Holocene fluvial deposits indicate periods of fluvial aggradations at approximately 19–23 ka, 10–12 ka, 3–5 ka, 0.9–1.2 ka BP, and 300 years ago (Lancaster, 2002).

The Kuiseb River is the most thoroughly studied river in the Namib Desert. The deposits and terraces of the Kuiseb River have been studied by a series of researchers (Rust & Wieneke, 1974, 1980; Marker, 1977; Marker & Muller, 1978; Vogel, 1982; Ward, 1987; Heine, 1985). The Homeb Silt deposit, which has been interpreted as a slack water deposit (Heine & Heine, 2002), occurs in the Kuiseb Valley upstream of Gobabeb. Radiocarbon dates from the Homeb Silt range between 23 and 19 ka BP. The Gobabeb Gravel deposits overlying the Homeb Silt date to 9.6 ka BP, indicating a period of Holocene aggradation (Vogel, 1982). The depositional environment and origin of these deposits have been discussed elsewhere, it remains unclear, however, whether such aggradations indicate a humid period or a dry period.

The aim of this study was to investigate the paleohydrological environmental history of the Kuiseb River. The landforms of the middle course of the Kuiseb River at Gobabeb are classified, and the soil profiles of each geomorphic surface are used to estimate the paleoenvironmental conditions. The ages of fluvial terraces are dated, using radiocarbon dating and dendrochronology.

Desertification has become the most important environmental problem facing Namibia. The descent of the groundwater level and the accompanying decline of riparian vegetation along the Kuiseb River have been reported in recent years (Mizuno & Yamagata, 2003). The processes of the area's paleoenvironmental changes should be very helpful in evaluating the present environmental problem.

RESEARCH AREA

The Kuiseb River is one of the major rivers rising in the interior highland and crossing the Namib Desert (Fig. 1). It is an ephemeral river, flowing only after sufficient rain has fallen in the catchment area. This river marks the border between the sand desert to the south and the rock desert to the north, as the temporal floods tend to wash out the dune sand advancing from the south (Fig. 2 & 3). The underflow water of the Kuiseb River creates a narrow oasis along the river. Due to these conditions, several types of environments adjoin the narrow riverside area.

Most previous studies have investigated the Kuiseb Canyon in the upper river basin. This study investigates the area around Gobabeb, along the middle reach of the Kuiseb River, about 60 km inland from the Atlantic coast. The study area lies at the mouth of the canyon, where the fluvial terraces and present flood plain are well developed (Fig. 2 & 3). Under these geomorphic conditions, the riparian forest should be strongly affected by the fluctuation of the

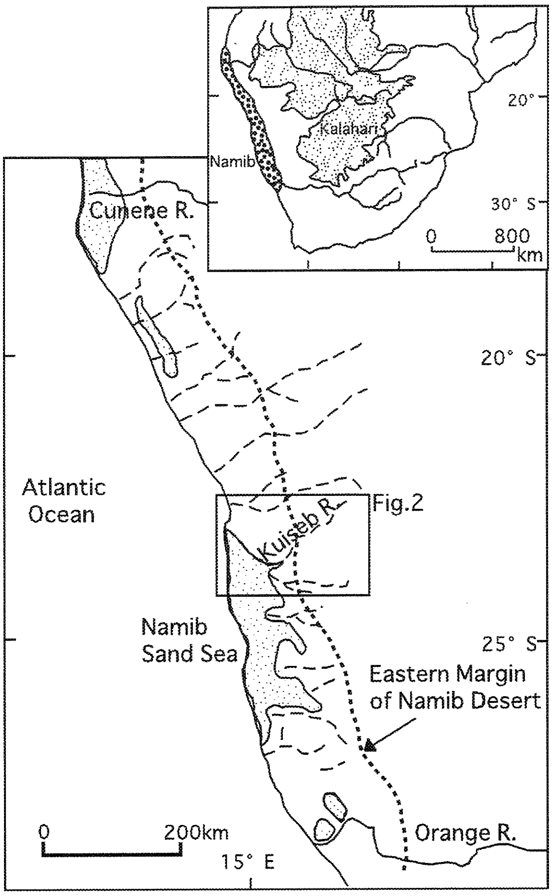

Fig. 1. The Namib Desert, showing major drainages, dune areas (dotted area), and location of study area (quadrangle area). Shaded area of Kalahari in the inserted map shows the distribution of the Kalahari Sand. (adapted from Thomas and Show, 1991)

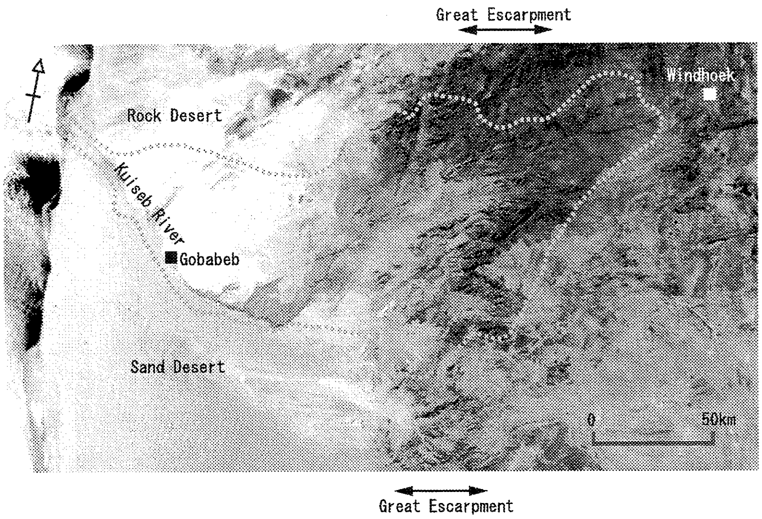

Fig. 2. CORONA satellite photograph of the Kuiseb River marking the boundary between sand desert and rock desert. (Imagery supplied by USGS; 1963/08/29)

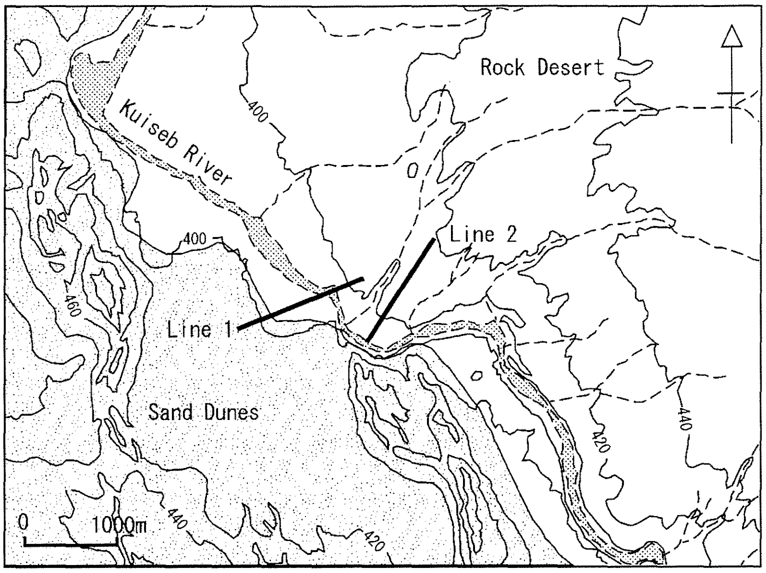

Fig. 3. Topographic map of the study area. Lines indicated are survey lines.

ground water level, making the locality particularly suitable for studying land-form development and environmental change.

TERRACE SURFACE AND DEPOSITS

Two survey lines were set across the Kuiseb River valley, from which two topographic profiles were drawn. Similarly, soil profiles along the survey lines were observed at points along each geomorphic surface.

The topographic profile of line 1 is illustrated in Fig. 4. The three terraces are classified as Lower (L), Middle 1 (M1), and Higher (H). Although this region receives only 27 mm of annual precipitation, the underflow water of the Kuiseb River nurtures a riparian forest that is developed primarily on the present floodplain and L surface. In contrast, there is almost no vegetation on the M1 and H surfaces. Small sand dunes are formed on the boundary between the terrace L and M1 surfaces, while large-scale linear sand dunes develop on the H surface. Because river-borne gravel deposits are recognized on the H surface, this surface is considered to be a fluvial surface.

On the other hand four terraces are recognized in the topographic profile of line 2 (Fig. 4). Of those terraces, three correlate with the L, M1, and H surfaces, based on the relative height of the terraces from the present riverbed, and on the characteristics of the soil profiles. With the new classification of the Middle 2 (M2) surface, a total of four terrace surfaces are identified in the study area, of which three (L, M1 & M2) develop only around this region. The H surface appears to continue through to the Great Escarpment and on to the Atlantic coast.

The columnar sections of surficial deposits on each terrace are shown in figure 5. Deposits on the L, M1, and M2 surfaces are mainly composed of

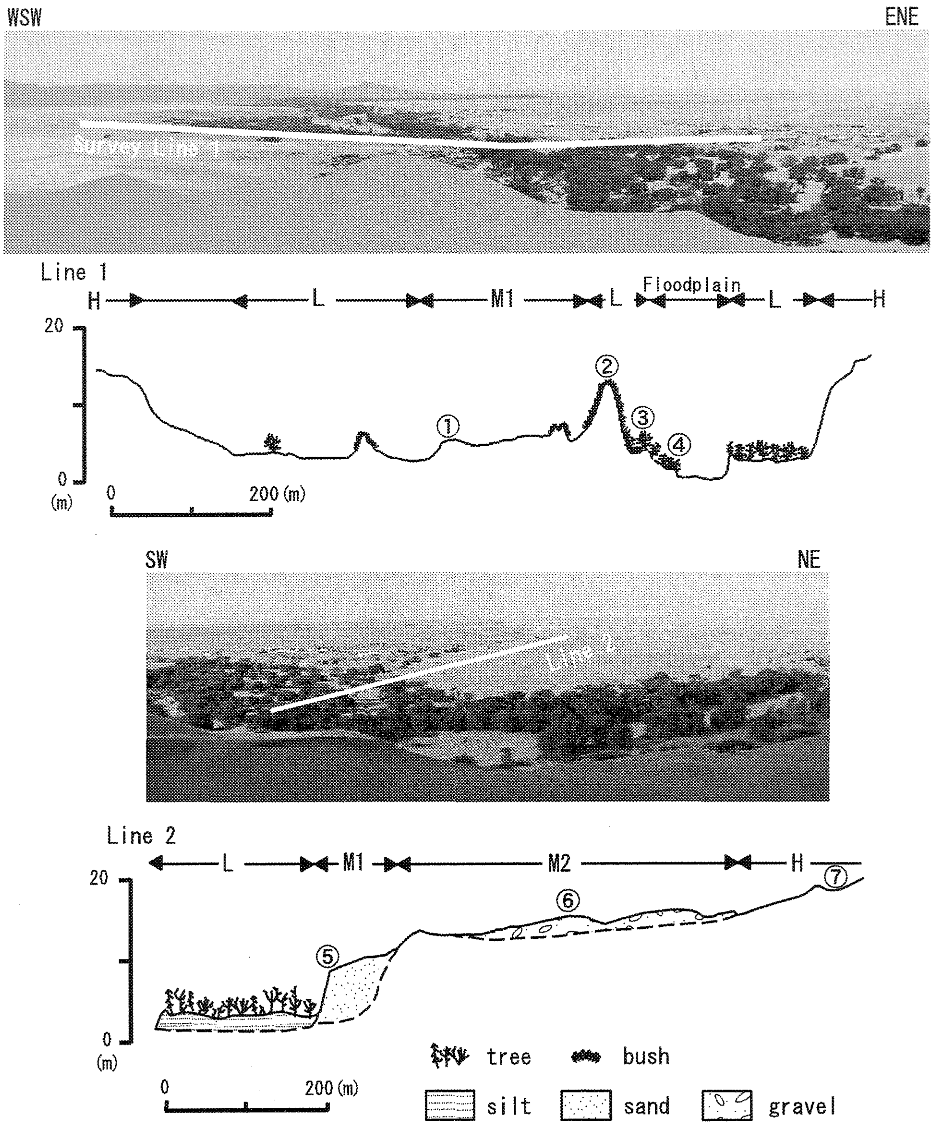

Fig. 4. Panorama views of the study area with the survey line and topographic profiles along the survey lines showing the distribution of the vegetation and locality of geological sections.

sandy deposits, and include stratified silt layers in some places. On the M2 surface, a gravel layer containing pebbles of about 2–4 cm in diameter occurs at the top of the deposit (Fig. 5–6). The most part of the H surface is exposed rock, but as some partial gravel deposits are recognized here, it is confirmed as a fluvial surface.

The difference in height between the present floodplain and the L surface is less than 1 m, but thick litter deposits are recognizable only on the L surface (Fig. 5). This supports the conclusion that the L surface is older than the present floodplain.

Duricrusts have clearly formed on the M1 and H surfaces, and are somewhat developed on the M2 surface. However, no duricrust is present on the L surface or the present floodplain. Figure 6 shows the duricrust on the M1 and H surfaces; the color and shape of the two duricrusts differ markedly from each

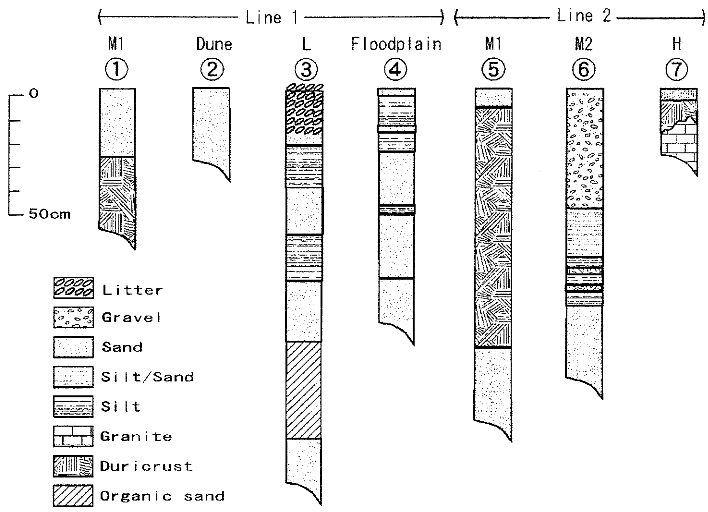

Fig. 5. Soil profile along survey line 1 (①−④) and line 2 (⑤−⑦). The localities are shown in Fig. 4.

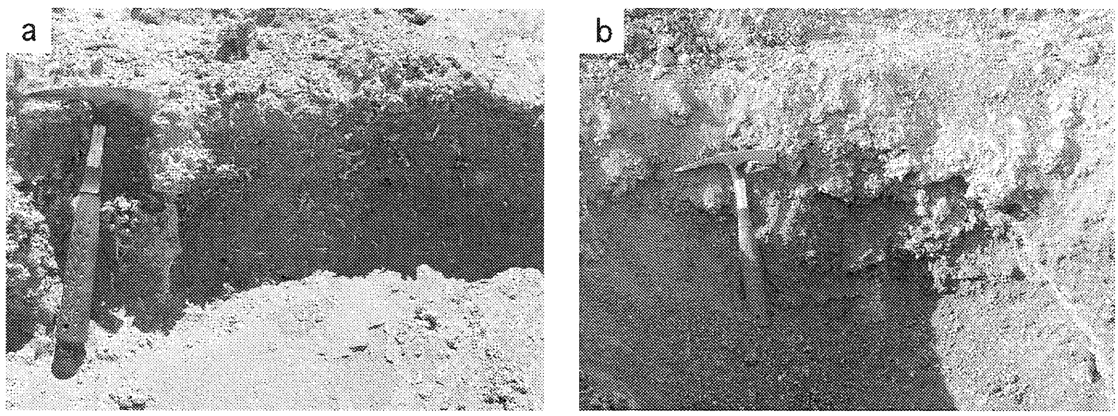

Fig. 6. Duricrust on the M1 and H surfaces.
(a) Duricrust on the M1 surface, (b) Duricrust on the H surface.

other.

In order to determine the mineral composition of duricrust, x-ray diffraction analysis was performed on the orientated samples of the clay fraction, which was separated from crushed samples by centrifuge. Figure 7 illustrates the x-ray diffraction patterns of the deposits. The diffraction patterns clearly show that the deposits on the M1 surface contain calcite, while the deposits on the H surface contain gypsum. The deposit on the M2 surface also contains a small amount of calcite. Therefore, the duricrust formed on the M1 surface is identified as calcrete, and the duricrust on the H surface is identified as gypcrete. The deposits on the present floodplain contain no calcite or gypsum, but do contain clay minerals such as illite and chlorite, derived from the process of rock weathering.

The absence of calcrete on the present riverbed suggests that the M1 and M2 surfaces were formed under different conditions from those that pertain to the present time. Calcrete formed near the surface by the accumulation of calcium

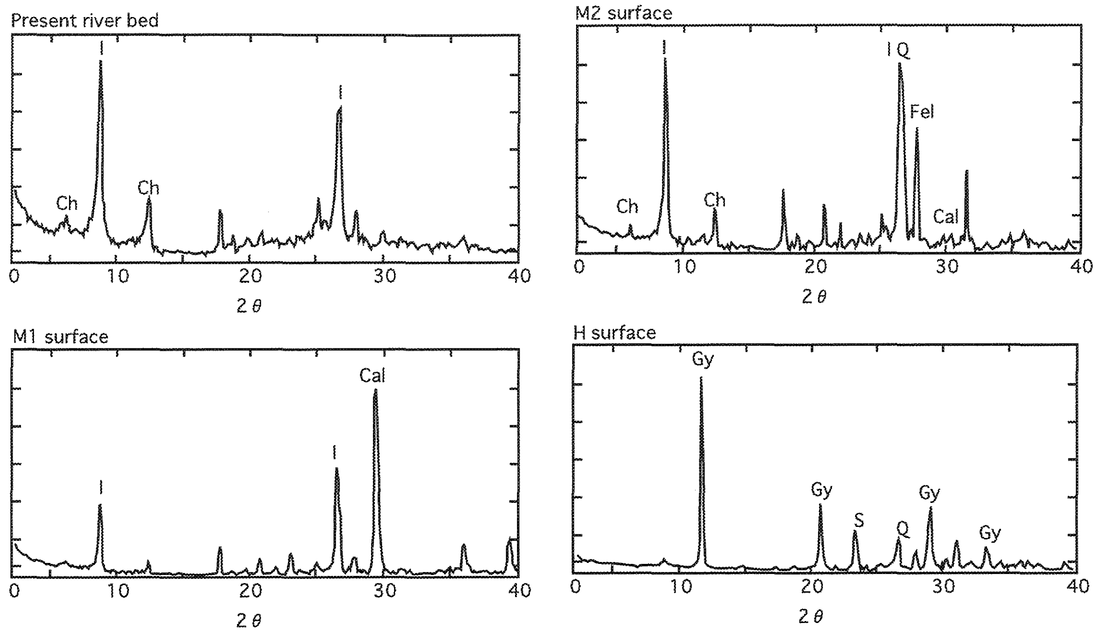

Fig. 7. X-ray diffraction pattern for terrace deposits.
Ch: Chlorite, I: Illite, Gy: Gypsum, S: Sulphate, Q: Quartz, Fel: Feldspar, Cal: Calcite.

carbonate, deposited by capillary rise and evaporation. Because water must be present in the soil to evaporate, the groundwater level was assumed to have been at a higher level than at present.

Although the M1 surface currently supports no vegetation, the calcrete on the M1 surface appears to have precipitated around the roots of plants (Fig. 6). This suggests that the M1 surface was originally covered with vegetation, which covered an area much larger than the present riparian forest.

AGES OF THE TERRACES

Calcrete contains carbonate, which allows the use of radiocarbon dating. However, this method may not yield an accurate date for the material owing to contamination of the sample by younger carbonate. On the other hand, this means that the radiocarbon dating of calcrete generally yields the youngest possible age. The calcrete formed on the fluvial terraces in the study area is thought to have formed within a short period of time. When the river floor terraced, the surfaces were separated from the underflow water of the Kuiseb River, causing calcrete formation to cease. The fact that the calcretes on the M1 and M2 surfaces formed weakly around the roots of plants supports the theory that they formed over a brief period of time (Fig. 6a). It is therefore concluded that the age of the calcrete yields the substantially accurate age of the terraces.

Radiocarbon dating of the calcrete was performed to determine the age of the terraces, and the ages obtained are shown in Table 1. Conventional radiocarbon ages of 5,300±60 years BP and 6,450±50 years BP were obtained for the

Table 1. Radiocarbon dates of samples (conventional ^{14}C age).

Surface	Material	^{14}C data (years BP)	Laboratory code number
L	Wood	300±60	Beta-165889
M1	Calcrete	5,300±60	Beta-164939
M1	Calcrete	6,450±50	Beta-176921
M2	Calcrete	22,070±260	Beta-176922

calcrete on the M1 surface, and an age of 22,070±260 years BP was obtained for the M2 deposit.

The dead trees buried by sand dunes on the L surface were dated to 300±60 years BP and 550±50 years BP. Samples for dating were taken from the surface of the tree trunk, and the age of the L surface was determined to be about 300 to 600 years old. Dendrochronological techniques were also used to fix the age of the L surface. Several large-diameter trees were cored, and their ages were calculated to range from about 300 to 600 years old.

The base diameter distribution of the trees on the L surface was measured (Fig. 8). Under ordinary circumstances, the distribution pattern should show that younger trees are more numerous. But the results indicate a marked deviation at a diameter of 20–30 cm (Fig. 8). In fact, young trees and seedlings are not evident in the forest, suggesting that the riparian forest formed during the past humid period of about 300–600 years ago, and that the forest has terminated the regeneration since the L surface terraced.

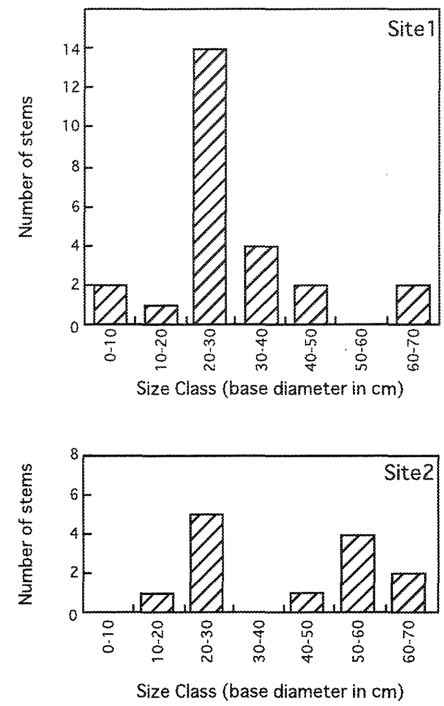

Fig. 8. Size distribution of riparian forest trees on the L surface.

PALEOENVIRONMENTAL AND PALEOHYDROLOGIC CHANGES IN THE MIDDLE COURSE OF THE KUISEB RIVER

Paleoenvironmental changes along the middle course of the Kuiseb River can be reconstructed on the aforementioned results as follows: The M2 surface formed ca. 22 ka of the last glacial maximum. This period was likely to have been more humid than the present, leading to a considerably higher rate of sediment generation, resulting in the formation of a relatively high depositional surface. A drier period probably followed this period, followed in turn by a more humid period at about 5–6.5 ka. The depositional surface (M1) formed in the valley and was covered by vegetation during this period. Simultaneously, the calcrete precipitated on the surface via the capillary rise of the shallow groundwater. During the subsequent drier period, this vegetation retreated. About six hundred years ago, the climate once again became more humid, and the present riparian forest was established. The most recent aridification began about 300 years ago, and led to the decline of the riparian forest and an increase in dune formation.

It is problematical whether this evidence indicates an increase in precipitation in the Namib Desert. The gypsum in the Namib Desert was probably formed by the deposition of atmospheric sulphate derived from the Atlantic Ocean (Eckardt & Spiro, 1999). The presence of a water-soluble gypsum crust on the H surface suggests that a significant increase in rainfall did not occur during the late Quaternary period. Therefore, the paleohydrologic environment of the terrace-forming periods probably involved increased rainfall in the interior highland east of the desert, rather than in the desert itself (Heine, 1998).

The previous chronology of the environmental change in southern Africa is shown in Fig. 9. The data from basin, lake, pan, and river in the inland Kalahari Desert record a humid period of 20–25 ka, during the last glacial age, a date that is in common with the records present in the Kuiseb River (Fig. 9-a). However, evidence of humid periods between 10–20 ka and around 40 ka does not appear in the Kuiseb River. Holocene environmental change has been examined in the Namib and Kalahari deserts, and within a marine core taken from off the coast of the Namib Desert (Fig. 9-b). The humid period of around 6 ka was recognized as a distinct humid event in the Kalahari Desert, but the humid period of 2 ka and 4 ka recorded in the Kalahari Desert is not evident at the Kuiseb River. In addition, evidence of humidification during the Little Ice Age has not been obtained from the Kalahari Desert. Therefore, it seems that there were some humid periods, identifiable not only in the Kalahari Desert, but also in the Namib Desert. This leads to the conclusion that the three humid periods identified in this study (ca. 20 ka, 5–6.5 ka, and 300–600 years BP)

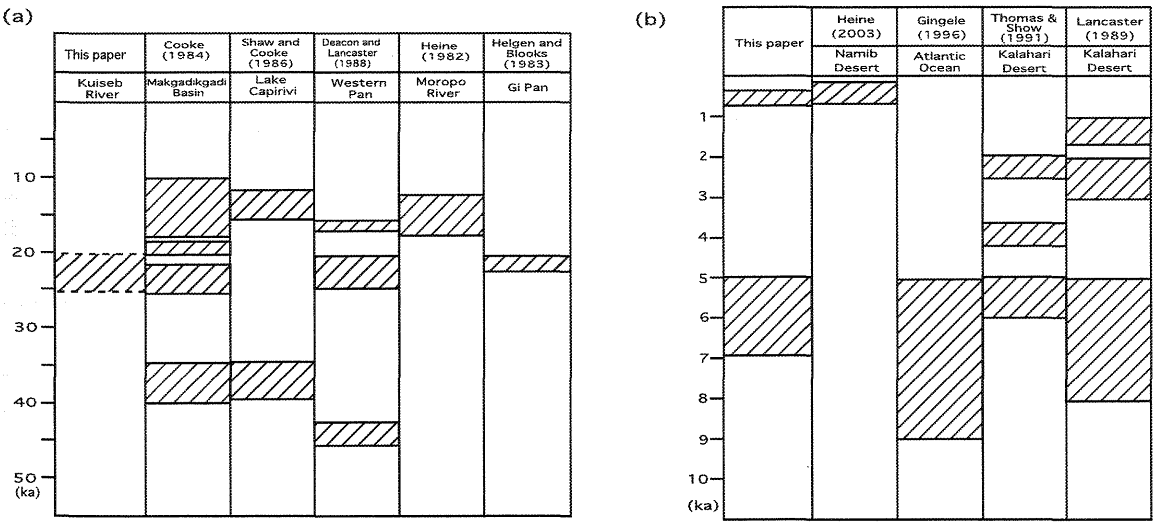

Fig. 9. Chronology of environmental change in southern Africa proposed by various authors. (a): The humid period of the Last Glacial Age in the Namib and Kalahari Deserts, (b): The Holocene climatic change in southern Africa.

were intensive enough to influence the Namib Desert.

SUMMARY

1. The four terraces L, M1, M2, and H were classified in the vicinity of Gobabeb along the middle course of the Kuiseb River.
2. The ages of the terraces were estimated by radiocarbon dating of calcretes and dead trees on these surfaces, and through dendrochronological data of the riparian forest on the L surface as follows: L surface: 300–600 years BP; M1 surface: 5–6.5 ka M2 surface: ca. 22 ka.
3. The formation of calcrete on the M1 and M2 surfaces and the establishment of the riparian forest on the L surface suggest that the terrace-forming periods were more humid than at present.
4. The presence of water-soluble gypsum on the H surface demonstrates that humidification did not occur in the Namib Desert, but in inland along the upper stream of the Kuiseb River.

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ENVIRONMENTAL CHANGES IN RELATION TO TREE DEATH ALONG THE KUISEB RIVER IN THE NAMIB DESERT

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ABSTRACT The Namib Desert is located along the western coast of Namibia and is affected by the cold Benguela Current. Although forest is distributed along the Kuiseb River in the Namib Desert, many trees are almost dead in some areas. The aim of this research was to clarify the relationship between environmental changes and tree death. The results of the survey are summarized as follows: (1) Many dead trees are located on the riverbanks made of dune sand, which are about 1 m high. (2) Dead trees are located in transitional areas where a northward protrusion of the southern shore is followed by a southward protrusion of the northern shore along the course of the river, in proximity to a sand dune. (3) Floods have eroded the noses of advancing sand dunes of the upper stream and have caused tree death by depositing sand. (4) The date of tree death has been estimated between the late 1970s and the early 1980s by ^{14}C dating. (5) Flood days numbered 33 per year from 1962 to 1975 and 2.7 from 1976 to 1985. The remaining thick sand layer, deposited by the last flood, may be the cause of tree death, given that there was drastic decrease in floods since 1976. (6) Tree death has greatly affected people's lives along the Kuiseb River because they depend on riverside forests as a source of shade, shelter, fuel, and food for humans and livestock.

Key Words: Kuiseb River; Namib Desert; Tree death; Flood decrease; Sand deposits; Humans.

INTRODUCTION

In Namibia, a country that contains a large desert area, desertification is a serious problem because it directly affects people's lives. Indicators of desertification in Namibia include the lowering of groundwater tables, soil erosion, loss of woody vegetation (trees), loss of grasses and shrubs (i.e., bare soil), a decrease in preferred grasses and shrubs, bush encroachment, an increase in soil salt content (salinity), and a decrease in soil fertility (Seely & Jacobson, 1986).

The forests along the banks of the Kuiseb River in the Namib Desert are partially dead. A common characteristic of areas of tree death is that the riverbank (about 1 m in height) is composed of dune sand; additionally, the curvature of the river changes from a northward to a southward projection, and is close to sand dunes. It has been surmised that the tree death is relatively recent, in that trees' ages have been found to be fairly consistent, about 100 to 350 years, irrespective of their vital status. The aim of this study was to clarify the reasons for the recent tree death in this region and to present the characteristics common to such areas.

STUDY AREA AND METHODS

I. Study Area

The research was performed near Gobabeb along the Kuiseb River in the Namib Desert in August, November, and December 2002; in March, August, November, and December 2003; and in August 2004 (Figs. 1 & 2). In Gobabeb, although the annual rainfall is only 27 mm, fog-water precipitation is 31 mm (Lancaster *et al.*, 1984). Extending inland for tens of kilometers on many mornings, the fog is densest at an elevation of 300 to 600 m. The fog is at its densest and fog-water precipitation is at its greatest about 40 km inland from the coast, because the altitude of the Namib Desert gradually increases from the coast eastward. Fog arises, on average, 37 days per year (1976–1981) in Gobabeb and constitutes the most important water supply for animals and plants in the Namib Desert (Lancaster *et al.*, 1984). The daily mean temperature per month is highest (24.8°C) in March and lowest (17.6°C) in August, and annual mean temperature is 21.1°C (Lancaster *et al.*, 1984). More than 90% of the annual rainfall occurs in the rainy season, from January to April. The coastal area is cool; the highest monthly mean temperature, 17.7°C, is in February and the lowest, 12.9°C, is in October. The annual mean temperature is only 15.5°C, owing to the cold Benguela Current.

Fig. 2. Dead trees along Kuiseb River.

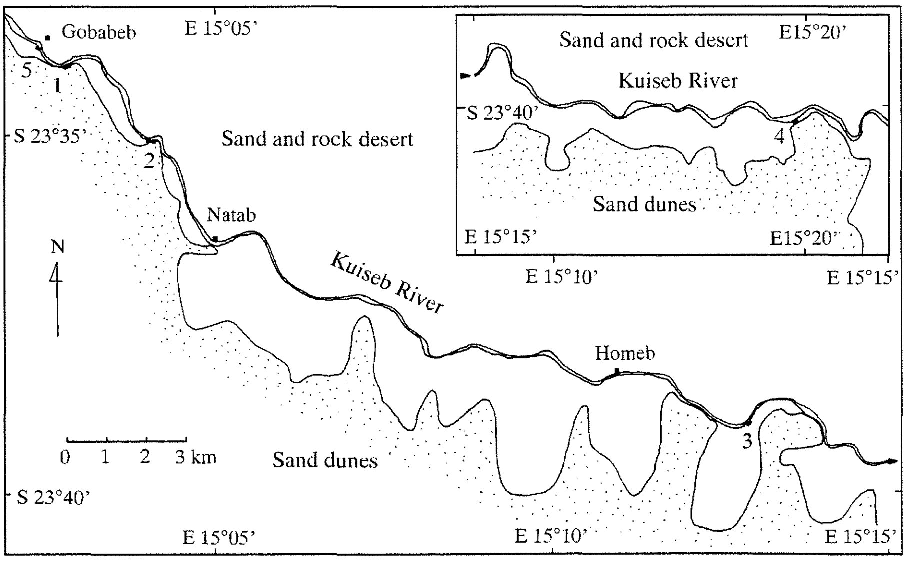


Fig. 1. Study sites. Sites 1–4: Sites with many dead trees; Site 5: Control site.

II. Methods

The study examined 50 km along the Kuiseb River; regions covered by many dead trees were investigated for their vegetation, topography, and soil. Quadrants were established for Sites 1 through 4 (Site 1: 100 m × 200 m; Site 2: 30 m × 210 m; Site 3: 18 m × 120 m; and Site 4: 25 m × 60 m), typified by extensive tree death; Site 5 (15 m × 75 m), however, was occupied by mostly healthy trees. Tree height and diameter at breast height of *Faidherbia albida* and *Acacia erioloba* were investigated for each quadrant. Although *Faidherbia albida* was formerly called *Acacia albida*, *Faidherbia* is quite different from *Acacia,* especially in terms of wood anatomy and pollen morphology, and the fact that it remains leafless for much of the wet season, only coming into leaf in the early dry season (Wyk *et al*., 2000). *Faidherbia albida* and *Acacia erioloba* were selected to investigate the relationship between tree height and diameter at breast height because they account for more than 90% of all trees in the study area and are morphologically similar. The quadrant of Site 1 was established to include the slope of the sand dune, a small terrace (i.e., river bank) formed by redeposit of dune sand, and the slope below the terrace. The quadrants of Sites 2 through 4 were established to include a small terrace (river bank) formed by dune sand.

Surface soil in the forest along the river is generally a dull yellowish brown (10YR5/3, 10YR5/4, and 10YR4/3), and the dune sand is generally a bright reddish brown (5YR5/6) to dull brown color (7.5YR5/4). Therefore, the depth of sand transported from the sand dunes can easily be obtained by measuring the distance from the land surface to the top of the dull yellowish-brown layer (10YR5/3, 10YR5/4, and 10YR4/3) (Fig. 21). In addition, the texture of the dull yellowish-brown soil (i.e., sandy loam) is quite different from that of the dune sand.

Tree diameters were measured at their bases in cases where the trees appeared partially buried. The vital status of trees was divided into four groups: healthy growing, unhealthy growing, dying, and dead. Assuming that the highest leaf rate of trees is 100%, a leaf rate of 20% to 60% denoted an unhealthy growing tree, and 0% to 20% denoted a dying tree. To take seasonal differences into account, these characteristics were assessed in both summer (November-December) and winter (August).

The distribution of vegetation at Site 1 was mapped using a measure, compass, GPS, and an infrared distance meter (Fig. 3). Topographic profile 1 was mapped by measuring 156 points along a 400-m transect, and Topographic profile 2 was mapped by measuring 97 points along a 500-m transect. Soil profile and soil water were measured in pits that were 1 to 2 m deep. Wood fragments were dated by ^{14}C (radiocarbon) dating methods. Soil water was measured in soil moisture by volume using a Hydro-sense soil moisture meter (Campbell Scientific Ltd.).

^{14}C dating was performed by Beta Analytic Inc., Miami, Florida, USA. Small samples (Table 1: samples 3–5, 8) were dated by accelerator mass analysis (AMS). The ^{14}C date is presented as conventional ^{14}C age. In the case of modern samples (samples 1–6) from 1950, the dates were obtained by comparison between

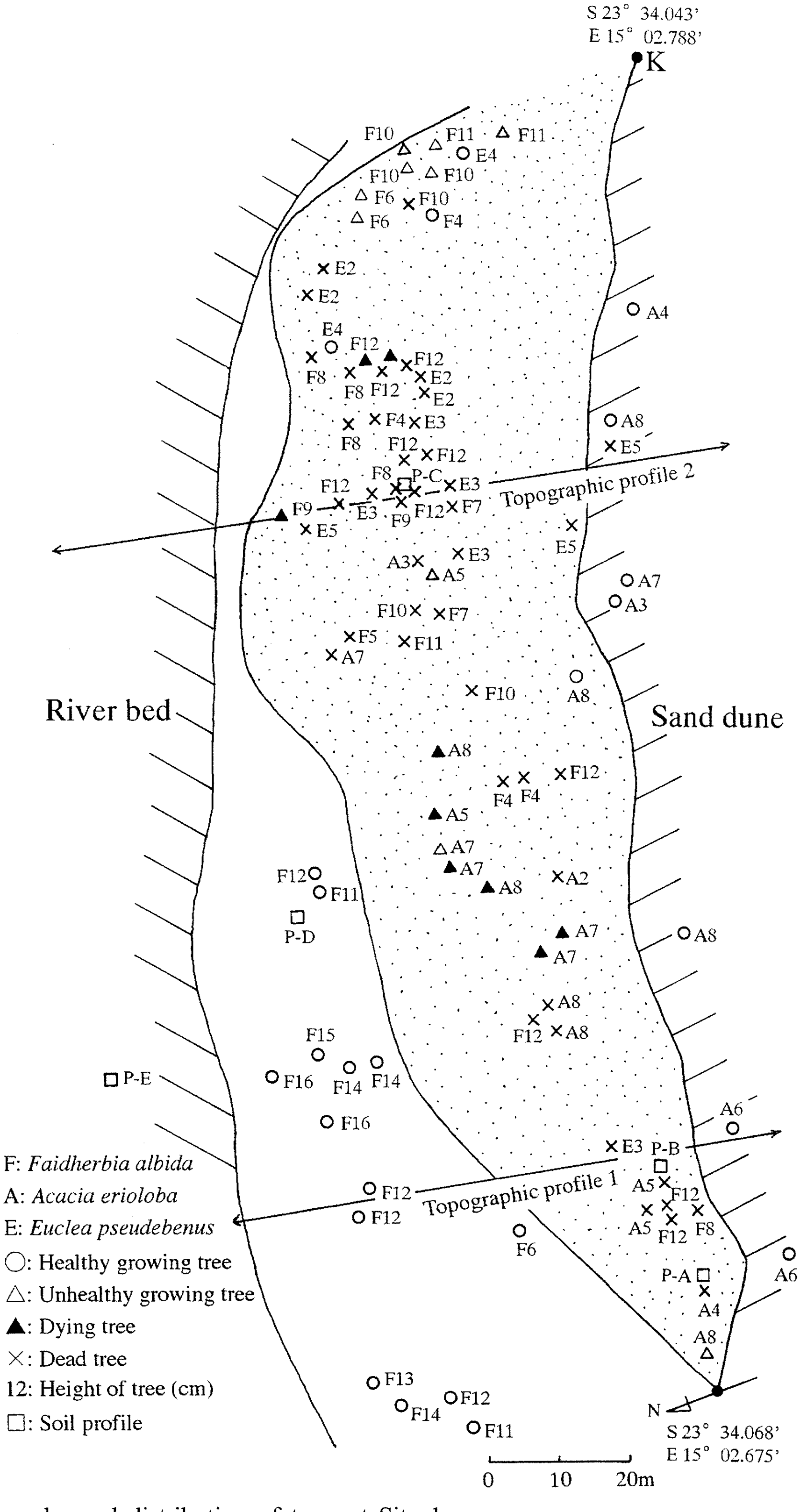


Fig. 3. Topography and distribution of trees at Site 1.
Dotted area denotes river bank composed of dune sand. K is a reference point used to measure movement of the sand dune. Classification of trees is the same as in Fig. 5.

Table 1. ^{14}C dates of tree samples (conventional ^{14}C age).

Sample number	Material	Meathod	^{14}C data (yr BP)	$\delta^{13}C$ (permil)	Laboratory code number (Beta-)
1	Wood	Radiometric	118.0 ± 0.7 pMC*	-28.4	170934
2	Wood	Radiometric	131.5 ± 0.8 pMC*	-24.5	170935
3	Wood	AMS	121.1 ± 0.5 pMC*	-26.2	170938
4	Wood	AMS	133.8 ± 0.7 pMC*	-26.9	170936
5	Wood	AMS	134.6 ± 0.7 pMC*	-26.4	170937
6	Wood	Radiometric	103.5 ± 0.7 pMC*	-25.4	170939
7	Wood	Radiometric	380 ± 90	-25.4	170940
8	Plant material	AMS	140 ± 40	-25.1	170941
9	Wood	Radiometric	220 ± 50	-26.3	170942

*: Modern (percentage is from the modern standard).
Radiometric: radiometric dating. AMS: Accelerator mass spectrometry.

the ^{14}C concentrations of wood fragments and global data (1950–2000) (Nakamura *et al.*, 1987; Levin & Kromer, 2002; etc.). (Fig. 22). This method assumes a global tendency for a gradual increase of ^{14}C concentration in the atmosphere owing to fission and fusion bomb detonation, coming to a peak in 1964–1965, and a decrease in atmospheric ^{14}C concentrations thereafter. Therefore, two dates, before and after 1964–1965, were identified from concentration values. For dating of the dead trees, the ends of branches were chosen, as they were the last to grow.

RESULTS AND DISCUSSION

I. Extensive Tree Death and the Environment

Figure 1 shows the locations of extensive tree death along the Kuiseb River; four such areas (Sites 1 – 4) were confirmed for a 50 km stretch along the Kuiseb River.

The distribution of dead trees at Site 1 (Fig. 4) is shown in Fig. 3. Trees growing on the small terrace appeared to be almost dead or dying. On both the slope below the terrace and the slope of the sand dune, the trees were still alive except for one *Euclea pseudebenus*. For the relationship between tree height and trunk diameter at breast height in healthy trees, values were bimodally distributed (i.e., low and high) (Fig. 5). Large trees were distributed on the slope below the terrace, and small trees were located on

Fig. 4. Dead trees at Site 1.

the slope of the sand dune. Trees growing on the slope below the terrace had a larger diameter than expected diameter for their height.

In the two topographic profiles along the transects, there are depressions between the terrace and the slope of the sand dune (Figs. 6 & 7). The soil profiles P-A, P-B, and P-C (Figs. 8 & 21) are clearly different in the color and soil texture from the alluvial deposits (Fig. 9) of the slope below the terrace (Figs. 6 & 7).

In the quadrant of Site 2 (30 m×210 m) (Fig. 10), although there are many

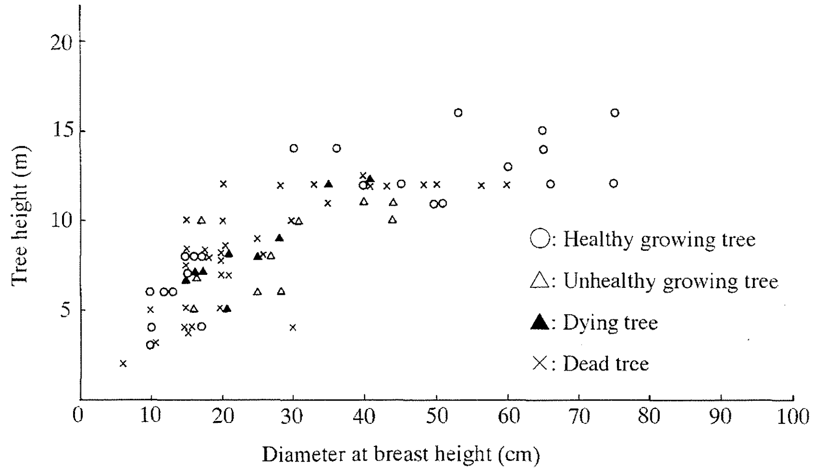


Fig. 5. Tree height and trunk diameter at breast height of *Faidherbia albida* and *Acacia erioloba* at Site 1. Vital status of trees was divided into four groups: healthy growing tree, unhealthy growing tree, dying tree, and dead tree. Assuming that the highest leaf rate is 100%, a leaf rate of 20% to 60% characterized the unhealthy growing trees and that of 0% to 20% characterized dying trees. To take seasonal differences into consideration, assessments were made in summer (November –December) and winter (August).

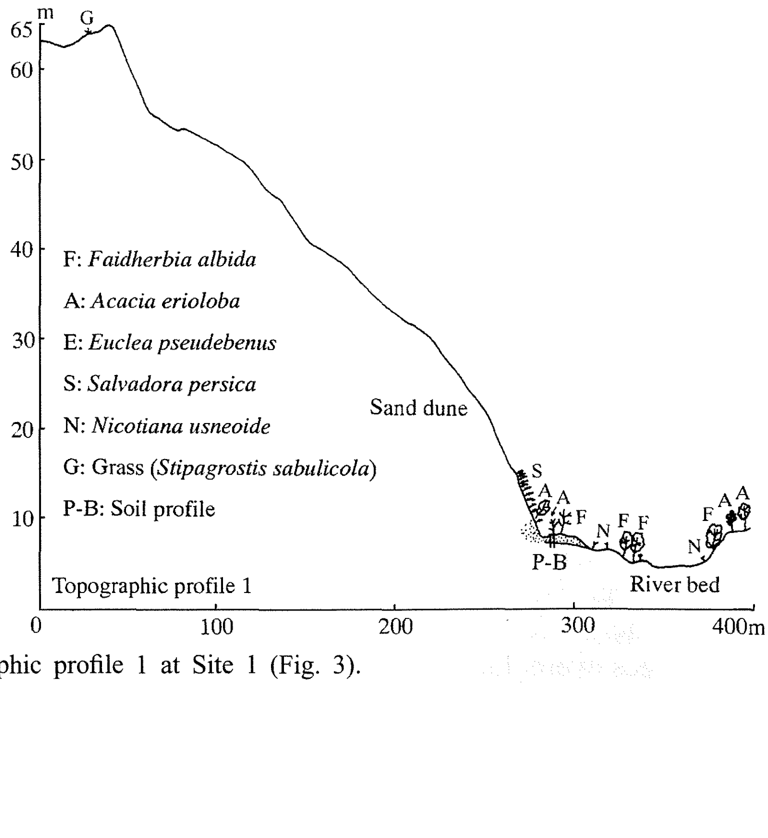


Fig. 6. Topographic profile 1 at Site 1 (Fig. 3).

dead trees, healthy trees appear to be growing well (Fig. 11). In the quadrant of Site 3 (18 m × 120 m) (Fig. 12), almost all of the trees appear to be dead, but two small growing trees appear to have regenerated recently (Fig. 13). In the quadrant of Site 4 (25 m × 60 m) (Fig. 14), it is thought that the forest may be reviving because regenerated trees are mixed among the dead trees (Fig. 15). In the control quadrant of Site 5 (15 m × 75 m), on the slope below the terrace, there are very few dead trees, and almost all trees are large in both height and diameter (Fig. 16).

At Sites 2 through 4, it appears that sand eroded from the sand dune has been deposited with the alluvial sediments, as assessed by an examination of the topography, soil color, and soil texture of the terrace occupied by dead trees.

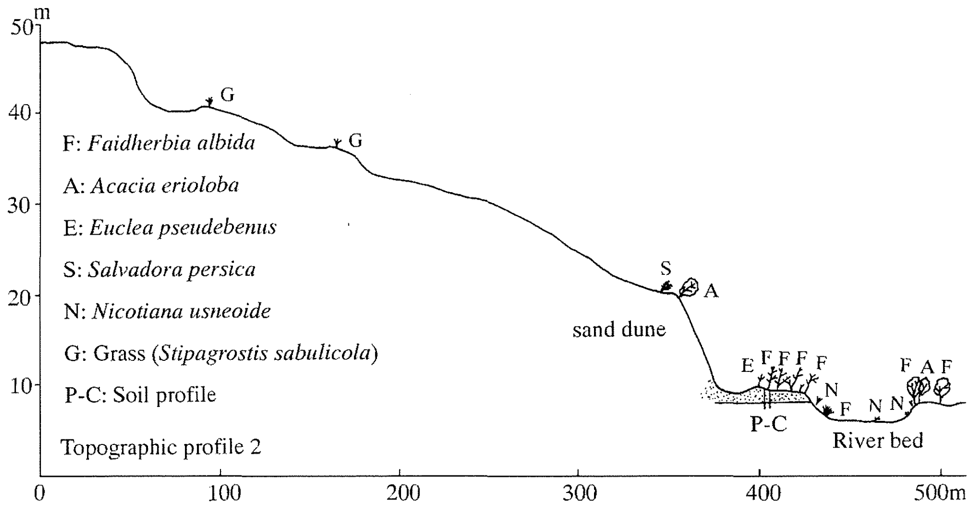


Fig. 7. Topographic profile 2 at Site 1 (Fig. 3).

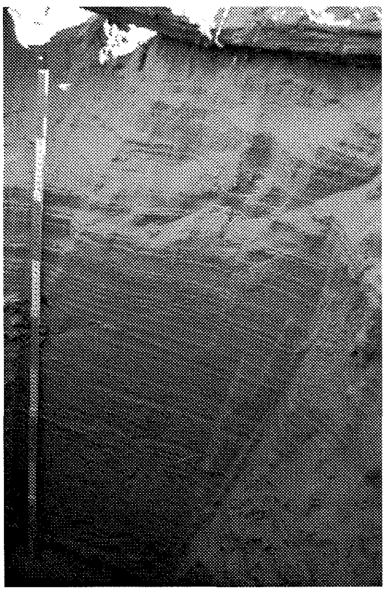


Fig. 8. Soil profile of the small terrace (river bank) composed of dune sand.

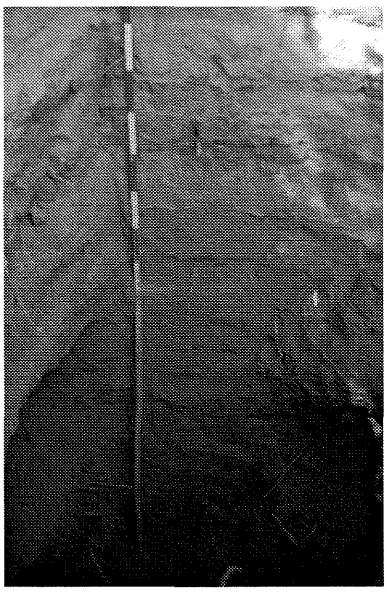


Fig. 9. Soil profile of the slope below the terrace (river bank).

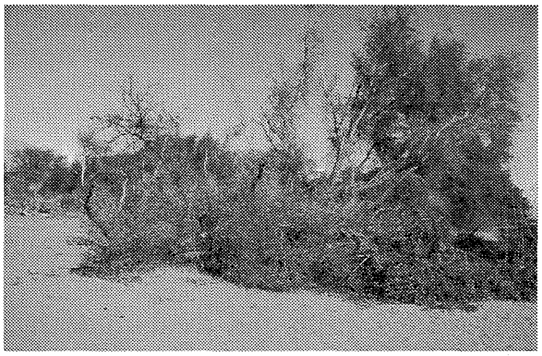


Fig. 10. Dead trees at Site 2.

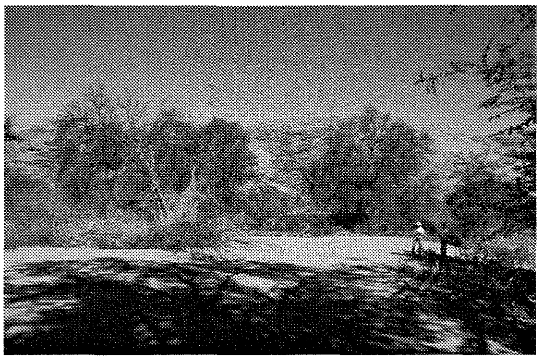


Fig. 12. Dead trees at Site 3.

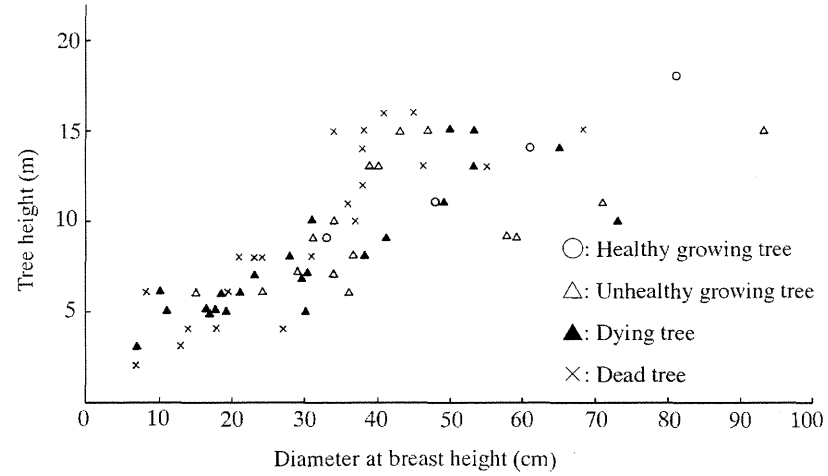


Fig. 11. Tree height and trunk diameter at breast height of *Faidherbia albida* and *Acacia erioloba* at Site 2. Classification of trees is the same as in Fig. 5.

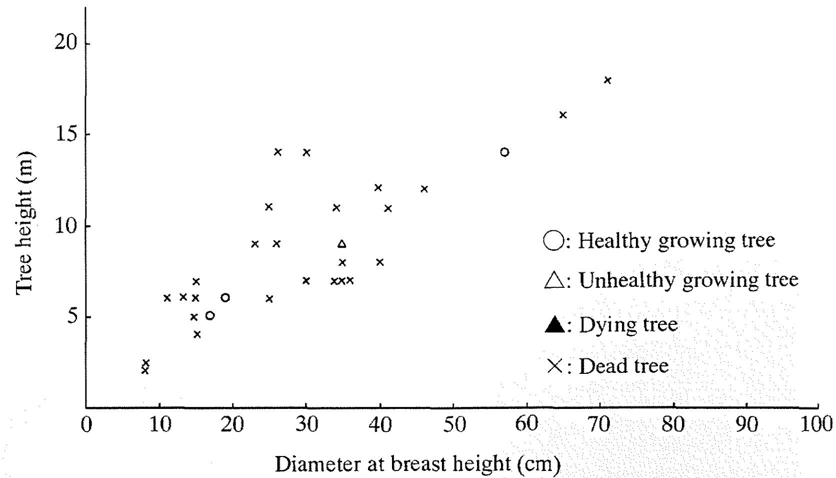


Fig. 13. Tree height and trunk diameter at breast height of *Faidherbia albida* and *Acacia erioloba* at Site 3. Classification of trees is the same as in Fig. 5.

II. Causes of Tree Death

Comparisons of areas with many dead trees at all four sites revealed a common characteristic: they are transitional areas where a northward protrusion of the southern shore is followed by a southward protrusion of the northern shore along the course of the river, in proximity to a sand dune (Fig. 1). It can be surmised that extensive tree death may have been caused by sand deposition resulting from flood formation of sand banks, from dunes projecting into the river, or by erosion of the noses of

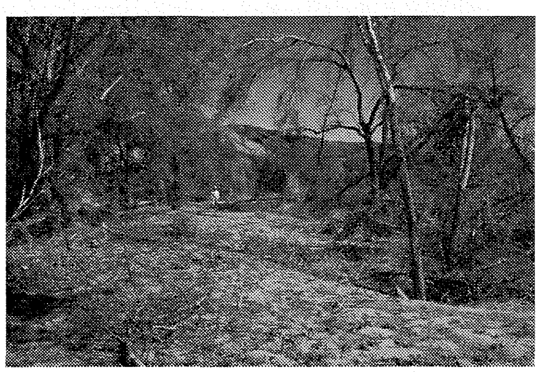


Fig. 14. Dead trees at Site 4.

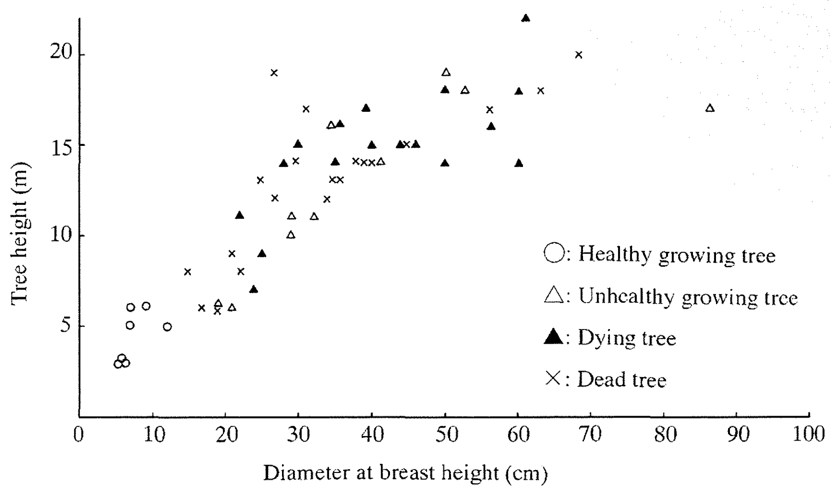


Fig. 15. Tree height and trunk diameter at breast height of *Faidherbia albida* and *Acacia erioloba* at Site 4. Classification of trees is the same as in Fig. 5.

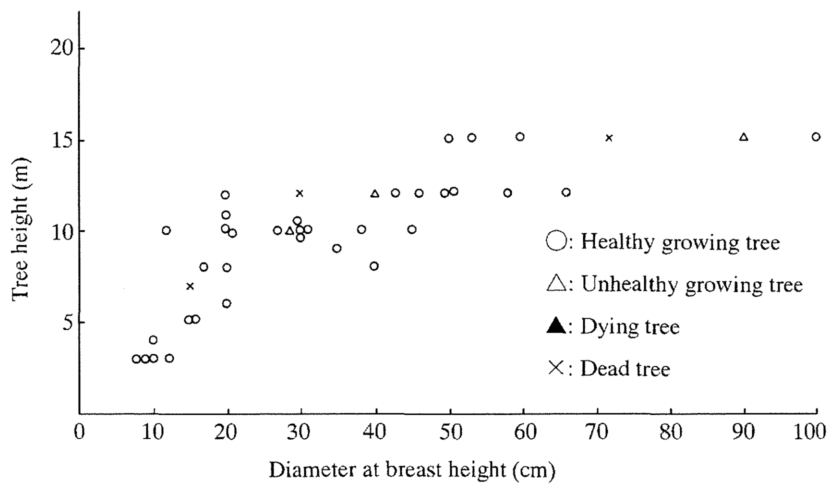


Fig. 16. Tree height and trunk diameter at breast height of *Faidherbia albida* and *Acacia erioloba* at Site 5 (control site). Classification of trees is the same as in Fig. 5.

Fig. 17. End of sand dune (point K, Fig. 5) (December 1, 2002).

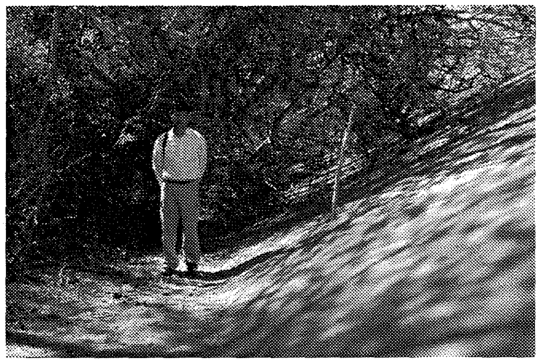


Fig. 18. End of sand dune (August 10, 2003).

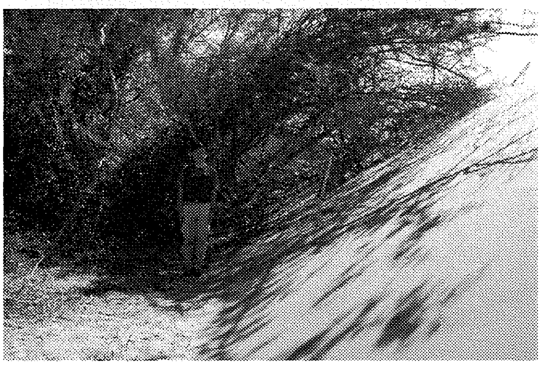


Fig. 19. End of sand dune (November 30, 2003).

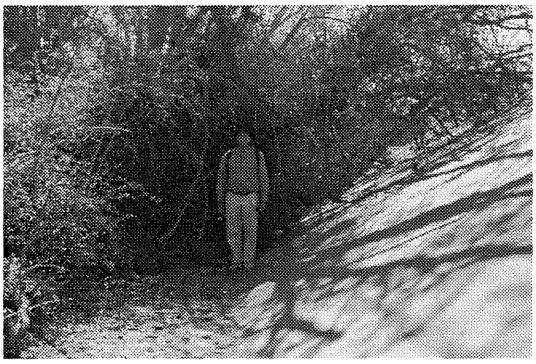


Fig. 20. End of sand dune (August 5, 2004).

advancing sand dunes and subsequent downstream deposition.

To monitor sand dune advance, a reference location was established at point K, as shown in Fig.3. A pole was planted at the end of a sand dune on November 29, 2002 (Fig. 17). By March 1, 2003, the pole was not buried at all and no sand dune movement was observed. By August 10, 2003, the pole was buried to a depth of 60 cm and the sand dune had advanced 100 cm horizontally (Fig. 18). By November 30, 2003, the pole was buried to a depth of 70 cm and the sand dune had advanced 145 cm from its initial position (Fig. 19). By August 5, 2004, the pole was buried to a depth of 130 cm and the sand dune had advanced 220 cm from its initial position (Fig. 20). Therefore, it was concluded that the sand had advanced discontinuously, and that its rate of advance was 120–145 cm/year (November 2002–August 2004).

The upper soil of the forest along the river was found to be a dull yellowish-brown (10YR5/3, 10YR5/4, 10YR4/3), and the soil of the sand dune was found to be bright reddish-brown (5YR5/6) or orange, or a dull brown (7.5YR5/4) (Fig. 21). Soil color thus can be used as an index of its origin. At Site 1, soil profiles from the terrace (river bank) formed by redeposit of dune sand (P-A, P-B, and P-C; Figs. 3 & 8), the slope below the terrace (P-D, Figs. 3 & 9), and the river bed (P-E, Fig. 3) were compared (Fig. 21). In profile P-A, bright reddish-brown (5YR5/6) sand deposits of a thickness of 70 cm were found to overlie dull yellowish-brown (10YR5/4) sandy loam. In profile

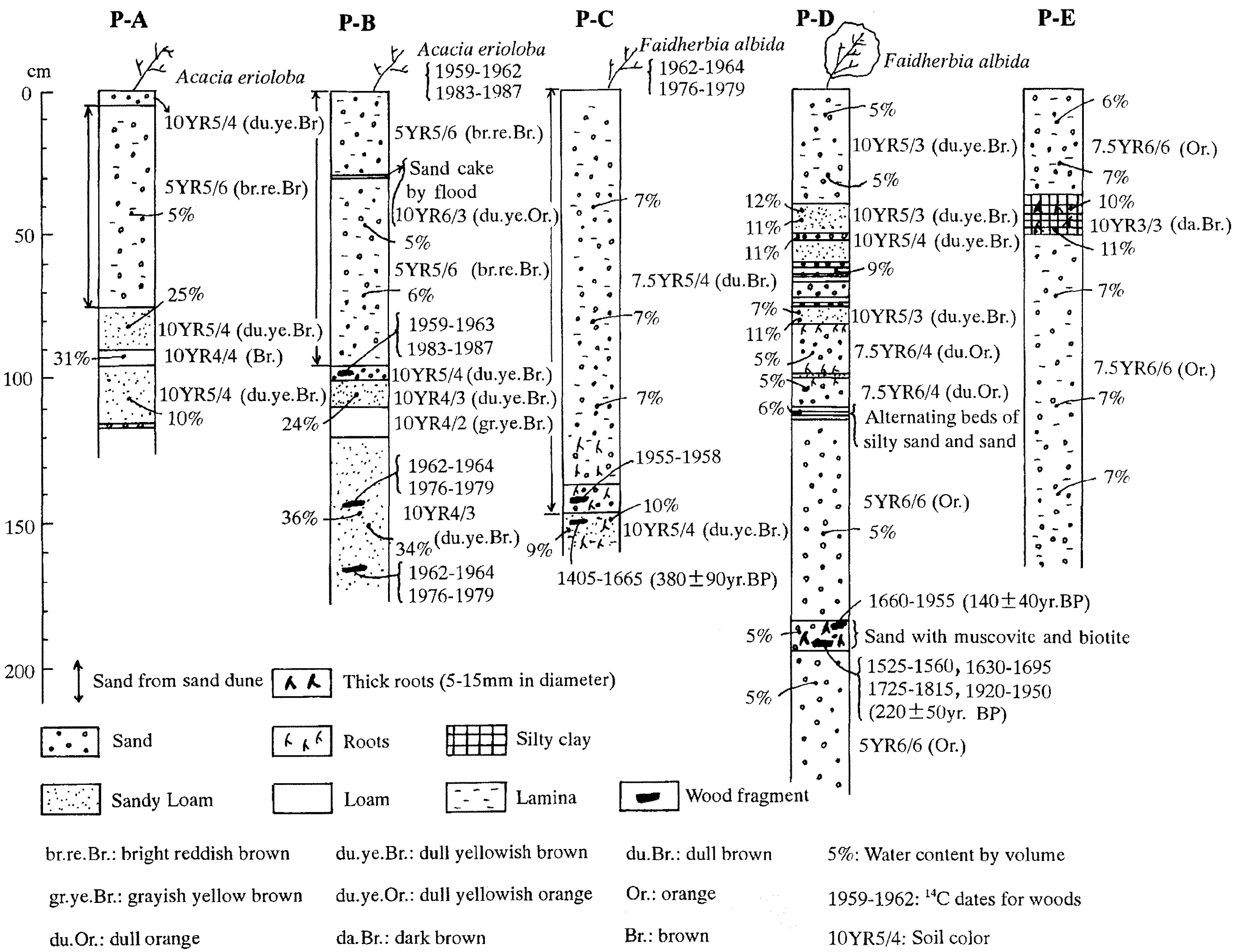


Fig. 21. Soil profiles at Site 1 (Fig. 3). P-A, P-B, P-C: Soil profiles in areas covered by dead trees; P-D: Soil profile in an area covered by healthy growing trees; P-E: Soil profile in the river bed.

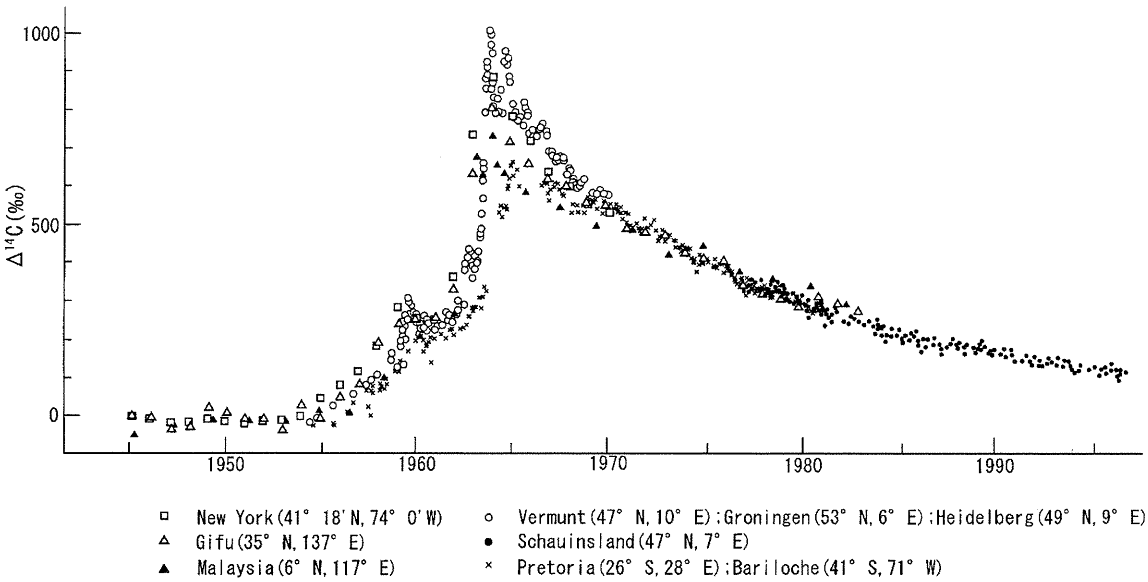


Fig. 22. Fission/fusion bomb-induced ^{14}C concentration variation in the global atmosphere.

Fig. 23. Adventive roots at 35-cm depth from the land surface.

P-B, bright reddish-brown (5YR5/6) sand deposits of a thickness of 100 cm were found, and the date of a wood fragment directly beneath the sand was estimated at 1959–1963 or 1983–1987 by ^{14}C concentration (Table 1, sample 3; Figs. 21 & 22).

The upper layers of soil profiles (P-A, P-B, P-C) including almost no litter suggest that the terrace has been recently formed by remarkable redeposit of dune sand (Fig. 21). The date of the dead trees was estimated as being 1959–1962 or 1983–1987 by ^{14}C concentration (Table 1, sample 1; Figs. 21 & 22). In soil profile P-B, it is reasonable to suggest that the sand was deposited over the wood fragment by floods in the 1960s to 1970s, from its date (1959–1963), and from the fact that the trees appear to have died from 1983 to 1987. In soil profile P-C, dull brown (7.5YR5/4) sand deposits of a thickness of 150 cm overlie dull yellowish-brown (10YR5/4) sandy loam. A wood fragment at the bottom of the sand layer had an estimated date of 1955–1958 by ^{14}C concentration (Table 1, sample 6; Figs. 21 and 22), and the date of dead trees was estimated at 1962–1964 or 1976–1979 by ^{14}C concentration (Table 1, sample 1; Figs. 21 & 22). In soil profile P-C, it appears that sand was deposited over the wood fragment by floods in the 1960s to 1970s, and that the trees died in 1976–1979. Although most trees on the terrace (bank) appear dead, some trees are not. One tree (Fig. 3, ΔA5) with relatively abundant leaves was found to have adventive roots at a depth of 35 cm from the land surface (Fig. 23). Adventive roots may play a protective role against tree death caused by sand deposition. This will be a subject of future research.

In soil profile P-D, where dune sand is absent, dull yellowish-brown (10YR5/3) soil can be observed and the trees are still alive. Although soil moisture (water content by volume) is below 10% in the sand layer from the surface to 70 to 150 cm in profiles P-A, P-B, and P-C of the terrace (bank) covered by many dead trees, it is over 10% at 40 cm deep in profile P-D (Fig. 21). In profile P-E of the river bed, orange (7.5YR6/6) sand can be observed.

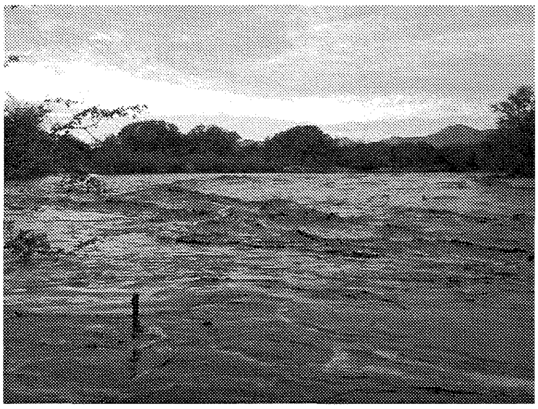
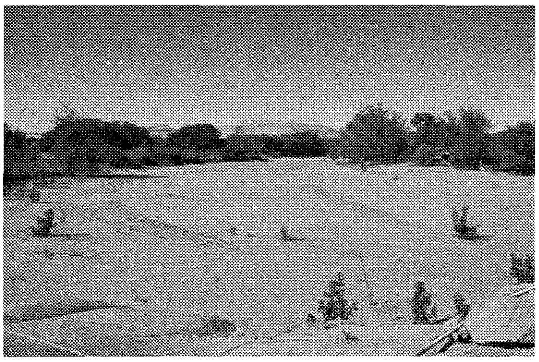


Fig. 24. Kuiseb River flood.
(January 18, 2004: by Andrea Schmitz).



Kuiseb River has usually no water.

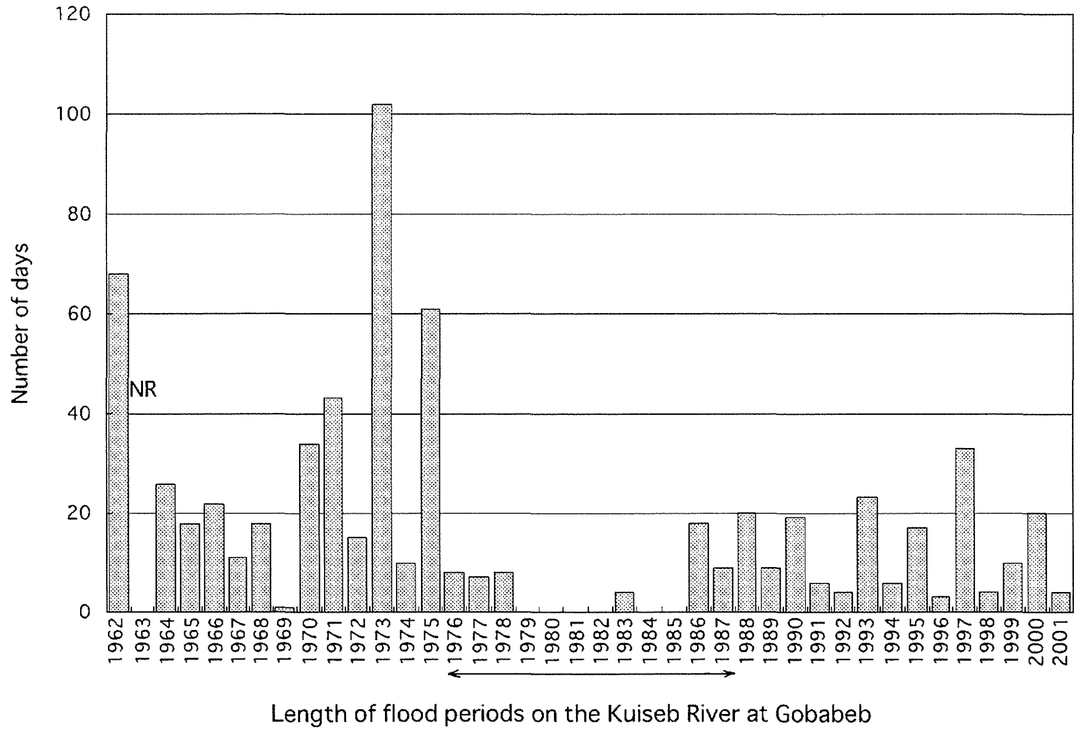


Fig. 25. Summary of Kuiseb River floods at Gobabeb, 1962–2001.
1962–1984: Seely *et al.*, 1981; Ward & Brunn, 1985. 1985–2001: from data of the Desert Research Foundation of Namibia.

III. Flood Fluctuations and Tree Death

In Gobabeb, the number of days of flood (all running water is regarded as flood) (Fig. 24) for the Kuiseb River was 33.0 days/year from 1962 to 1975. It was 9.2 days/year from 1976 to 2001, a decrease to one third of the 1962–1975 value (Fig. 25). The 1976–1987 date, estimated by ^{14}C methods as the date range of extensive tree death, coincides with the period when the number of flood days was very low. Until 1975, each successive flood washed away the sand deposited by the previous flood, and the trees did not die. For 12 years, from 1976 to 1987, the number of flood days decreased to 52 in total (4.3 days/year). For seven years, from 1979 to 1985, very little flooding occurred, and many trees died, perhaps because of sand deposition or a drop in the water table caused by a decrease in flooding.

CONCLUSIONS

The Kuiseb River in the Namib Desert marks the transition between stony desert and sand desert (i.e., sand dunes). Although forest is distributed along the course of the river, several areas are characterized by extensive tree death. These locations have the topography of small terraces (river bank), on which sand from dunes has been redeposited to a thickness of 1 m by flood. The upper layer of terrace indicates the same soil color and soil texture as the sand dune. Therefore, it is considered that sand of terrace is the materials redeposited from sand dune. The other characteristic common to all locations of extensive tree death is that they are in transitional areas where a northward protrusion of the southern shore is followed by a southward protrusion of the northern shore along the course of the river, and in proximity to a sand dune. It is reasonable to suggest that the cause of tree death has been sand redeposition from flooding, i.e., erosion of the advancing sand dunes and subsequent downstream sand deposition. The rate of sand dune advancement was measured at 120 to 145 cm/year for the period November 2002 to August 2004.

The dates of extensive tree death appear to be 1976–1987 by comparison of ^{14}C concentrations of the ends of dead tree branches and global ^{14}C concentration data (1950–2000). The dates of extensive sand deposition appear to be the 1960s to 1970s, as judged by the dating of wood fragments just underneath the orange sand layer. Although the number of days of flood at Gobabeb for the Kuiseb River was 33.0 days/year from 1962 to 1975, it was only 9.2 days/year from 1976 to 2001, a decrease to one third of the value in the period from 1962 to 1975. Until 1975, each successive flood appears to have washed away the sand deposited by the former flood, and the trees survived. For 12 years, from 1976 to 1987, the total number of flood days decreased to 52 (4.3 days/year); this period coincides with the dates of extensive tree death, as estimated by ^{14}C dating. For seven years, from 1979 to 1985, very little flooding occurred, and many trees died, perhaps because of sand deposition or a drop in the water table, owing to the decrease in floods.

The pastoral Topnaar people live along the Kuiseb River. The forest along the river provides shade, shelter, firewood, and food for goats as well as humans. The death of trees in this area is thus a serious problem. It is important, therefore, that the relationship between tree death and environmental changes be monitored and analyzed.

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TEMPORAL AND SPATIAL VARIABILITY OF GRASS PRODUCTIVITY IN THE CENTRAL NAMIB DESERT

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Enviroscience
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ABSTRACT The production of grass was investigated on the gravel plains of the Central Namib Desert, Namibia, during 10 rainfall seasons sampled between 1989–2003. The aim was to evaluate the rainfall-productivity relationship, to elucidate the relationship between temporal and spatial variability, and to examine the spatial scale of patchiness. We compared two different methods and found that a less accurate rapid assessment of grass cover correlated well with measurements of biomass. Our data were in agreement with previous determinations of the desert end of the curve of grassland productivity, and productivity was closely related to the rainfall of the particular season. There was high variability between years at study sites, especially in the west (CV=279%), where it rained more seldom than in the east (CV=86%). During all years rainfall was very patchy at a spatial scale of 5 km, which apparently reflected the storm path of individual rain clouds. Long-term monitoring should be continued in order to detect changes of pattern in this rainfall-driven system.

Key Words: Rainfall-productivity relationship; Rapid assessment; Grass biomass; Storm cloud size; Patchy rainfall.

INTRODUCTION

Tropical arid regions are characterized by high temporal variation of rainfall (Tyson, 1986; Nichols & Wong, 1990). Temporal variability of rainfall at a particular site is negatively correlated with mean rainfall, and the more arid a site, the higher the variability (Tyson & Dyer, 1975). Similarly, high spatial variability of rainfall characterizes arid regions (Sharon, 1981; Noy-Meir, 1981; Dean & Milton, 1999; Ward *et al.*, 2004). These patterns result in frequently-changing temporal and spatial concentration of primary production. The current study elucidates these responses along a steep gradient of aridity in the Namib Desert (Fig. 1).

Previous studies conducted in the Namib Desert demonstrate that temporal patterns of local rainfall affect abundance of plants and animals (e.g. Holm, 1970; Seely, 1973, 1978a, 1978b, 1990, 1991; Seely & Louw, 1980; Nel, 1983; Hamilton, 1985, 1986; Yeaton, 1988; Boyer, 1989; Berry & Siegfried, 1991; Günster, 1992; Southgate *et al.*, 1996; Henschel & Seely, 2000). It is also known that distribution of rainfall affects spatial patterns within the ecosystem

(Robinson, 1976; Seely, 1978a, 1978b; Tilson & Henschel, 1986; Günster, 1992, 1995; Brain, 1993; Kilian, 1995; Kok & Nel, 1996; Burke, 1997; Hachfeld, 2000). In the Central Namib, epiphenomena in the form of heavy rainfall events of >100 mm per annum have occurred only four times in a century (1934, 1976, 1978, 2000). In a first approximation, strong, rapid increases in abundance of many plants and animals were demonstrated (Seely & Louw, 1980). These big events can have effects that last for decades (Southgate *et al.*, 1996; Henschel *et al.*, in press). Winds that shift surface material blow for >50% of the time (Lancaster *et al.*, 1984), continuously redistributing detritus and renewing its availability on the surface, where detritivores feed on it (Crawford, 1979; Crawford & Seely, 1994).

Biomass of Namib plants is normally extremely low except at inselbergs (Burke *et al.*, 1998), in washes (Robinson, 1976) and in ephemeral rivers (Seely *et al.*, 1980; Jacobson *et al.*, 1995), as well as in the fog zone, where succulents and lichens increase primary productivity (Schieferstein & Loris, 1992; Hachfeld, 2000). Most primary productivity on the Namib gravel plains is in the form of ephemeral grasses that flush briefly after effective rainfalls from dormant seedbanks (Robinson, 1976; Seely, 1978a, 1978b; Günster, 1992, 1995; Jacobson, 1992, 1997; Burke, 1997; Hachfeld, 2000).

Rainfall in the Namib usually comes from isolated convective clouds, that are spaced widely apart (Sharon, 1981). Rainfall is unpredictable to the degree that the occurrence of effective rain stimulating plant growth cannot be predicted for any year (Pietruszka & Seely, 1985), nor any location (Sharon, 1981). Individual rain clouds moving from east to west across the Namib leave a green path of grass. The width and length of each rainfall path and the number of annual rainfall days varies greatly (Sharon, 1981; Burke, 1997; Ward *et al.*, 2004). Hence, adjacent locations may not have the same productivity in a given year, and, via the seedbank and accumulated detritus, this effect may be cumulative over the years.

In the current paper we elucidate the relationship between temporal and spatial variability in rainfall and plant productivity. In particular we determine the spatial scale across which variability in productivity is expressed in each season, and how this may introduce heterogeneity across an otherwise relatively homogeneous plain. We asked the following questions: (1) are rapid (grass cover) assessments good indicators for grass biomass, (2) what is the rainfall-productivity relationship in this desert, (3) what is the relationship between temporal and spatial variability, (4) what is the spatial scale of grass patchiness.

STUDY AREA

The study was conducted across the gravel plains of the Central Namib (Günster, 1995; Wilkinson, 1990; Henschel *et al.*, 2003) between latitude 22°58' S and 23°34'S, longitude 14°34'E and 15°43'E (Fig. 1). The study area extended from 9–125 km inland of the coast, and extended about 50 km from north to south. Altitude at study sites ranged from 27–1000 m above mean sea level (a.m.s.l.). This area crosses several climatic zones from west to east (Besler, 1972; Hachfeld, 1996; Henschel *et al.*, 1998; Lancaster *et al.*, 1984) and the study area was subdivided accordingly (Fig. 1).

The central Namib's gravel plains are characterised by wide expanses of plains, intersected by a network of drainage areas and shallower drainage lines and several inselbergs (isolated mountains). These inselbergs rise 10 to about 200 m above the surrounding plains. The gravel plains slope gently from the

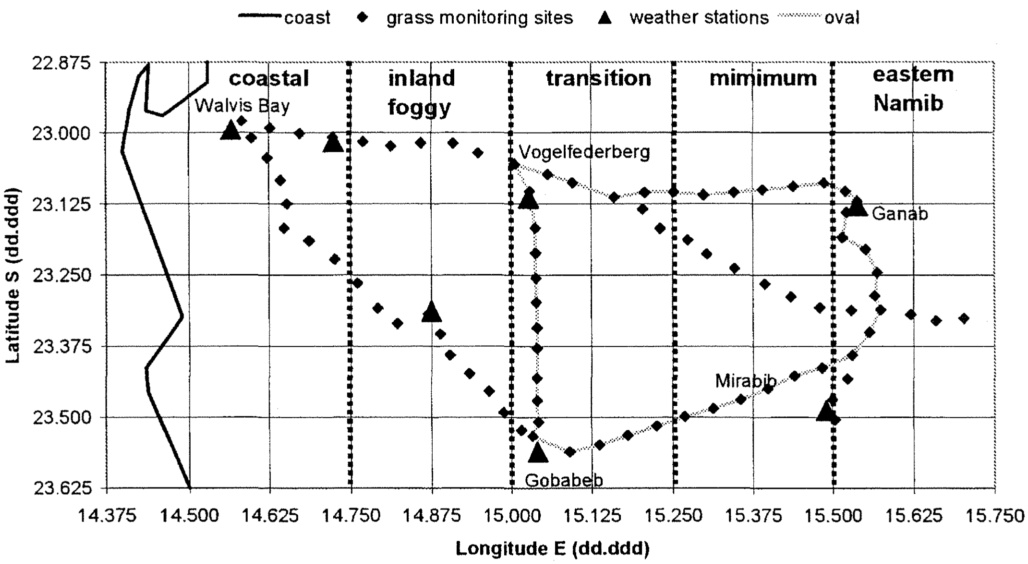

Fig. 1. Map of study area, showing position of 87 study sites, climatic zones, weather stations, and the Gobabeb-Mirabib-Ganab-Vogelfederberg oval of sites.

Table 1. Grasses recorded in the study area.

Aristida parvula	(Nees) De Winter
Brachiaria glomerata	(Hack.) A.Camus
Centropodia glauca	(Nees) T.A.Cope
Enneapogon desvauxii	P.Beauv.
Eragrostis annulata	Rendle ex Scott-Elliot
Eragrostis nindensis	Ficalho & Hiern
Stipagrostis ciliata	(Desf.) De Winter
Stipagrostis dinteri	(Hack.) De Winter
Stipagrostis gonatostachys	(Pilg.) De Winter
Stipagrostis hirtigluma	(Steudel ex Trin. & Rupr.) De Winter
Stipagrostis lutescens	(Nees) De Winter
Stipagrostis obtusa	(Delile) Nees
Stipagrostis subacaulis	(Nees) De Winter
Stipagrostis uniplumis	(Licht.) De Winter
Triraphis pumilo	R.Br.
Triraphis purpurea	Hack.

coast towards the east, with an increase in altitude from 0 to approximately 1000 m a.m.s.l. The soils on the plains are poorly developed calcisols and gypsisols, which are characterised by underlying calcrete crusts and high gypsum content in the fog zone (Fig. 1) (Scholz, 1972).

On a national scale the vegetation has been classified as Central Namib (Giess, 1971) and at a landscape level several grass communities were characterised (Nel & Opperman, 1985). We recorded 16 species of grass in the study area (Table 1).

CLIMATE

The study area contains 6 automatic weather stations of the Gobabeb Training & Research Centre (Fig. 1).

Most rain comes from summer monsoons. These come from the distant Indian Ocean, and rainfall becomes patchier as moisture decreases across the African continent. Only seldom do individual rain clouds cross westwards over the Namibian Great Escarpment and into the Namib. Therefore, rainfall decreases and temporal variability of rainfall increases from the Namib escarpment westwards towards the coast (Seely, 1978a, 1978b; Gamble, 1980; Sharon, 1981; Lancaster *et al.*, 1984; Günster, 1992; Mendelsohn *et al.*, 2002). Most rain falls during the hottest season between January and April (austral late summer). This period is followed by a dry period (May-August) dominated by berg winds. Relatively heavy precipitation of fog occurs in the western half of the Namib most commonly during the cool early summer (September–December).

METHODS

A network of 87 study sites, approximately 5 km distant from each other, was marked with GPS along 420 km of gravel roads crossing the Central Namib gravel plains (Fig. 1). The survey was conducted 2–3 weeks after the final rain of the season, i.e. during late April or early May. Between 1989–1995 changes in grass productivity were mapped along continuous transects bordering the roads and classified according to a visually-assessed index of grass cover (Günster, 1995; Burke, 1997) (Table 2). For comparison with later data, point

Table 2. Grass cover indices based on visual assessment of cover from a vehicle (following Burke 1997) compared to grass biomass

Index	% Grass Cover	Grass biomass ($g \cdot m^{-2}$)	Conversion of Index to Biomass ($g \cdot m^{-2}$)
0+	only in drainage lines	1–2	1
1	1–5	3–9	5
2	5–25	10–19	15
3	25–50	20–29	25
4	>50	>30	35

data for the 87 study sites were extracted from the transect data.

Between 2000–2003, grass productivity was measured as follows. From each marked site along a road, we walked off 60 m perpendicular to the road (S for E-W roads, W for N-S roads). There we determined a random spot by tossing a stone backwards across the shoulder away from the road. If the spot was unsuitable, the process of stone-throwing was repeated at another location 20 m parallel to the road. A spot was unsuitable if it fell into a drainage line, a rocky ridge or included a large perennial plant. We measured grass height and density with a point-frequency frame of 1 m width with guide holes at 1 m height (Mueller-Dombois & Ellenberg, 1974; Ward *et al.*, 1998). The point-frequency frame was positioned perpendicularly to the road with the closest leg standing on the designated spot. Then we took readings of grass height by lowering the ruler rod through a guide hole until its tip touched a blade of grass, and this height was measured (grass height). Ten measurements were recorded at 10-cm intervals and the average grass height was calculated. An area of 1 m^2 was demarcated with the point-frequency frame as mid-diameter, and all grasses inside this area were identified to species. The next spot was located 20 m parallel to the road (westwards for E-W roads, northwards for N-S roads). After measuring five spots on one side of the road, we measured another five spots 60 m off the other side of the road until the last spot was located opposite the first spot. The mean and CV of grass height from ten different spots (100 measurements) at a site constituted the measure of grass production and its patchiness at the site.

We compared grass height (cm) with above-ground oven-dried (60°C) biomass (range 1.424 – 46.294 $g{\cdot}m^{-2}$) of ephemeral plants clipped from 1 m^2 that surrounded the point-frequency frame at 53 sites in 2000. The following regression equation (r^2=0.85, p<0.001) was used to convert grass height to grass biomass ($g{\cdot}m^{-2}$):

$$grass\ biomass = 1.12 \times (grass\ height) + 2.79$$

At 60 sites in 2000, we simultaneously applied Burke's visual index of grass cover and measured grass height. This enabled us to combine the two data sets obtained with the index and by measuring grass height.

To determine the rainfall-productivity relationship data for a rainfall event in March 2000 were obtained from the Botany Department of the University of Hamburg, which maintains rain gauges located at 10 km intervals along the Walvis Bay–Kuiseb Canyon road. In April 2000, we determined grass biomass at 12 sites located <5 km from these rain gauges.

In order to establish the spatial scale at which grass biomass changed, sites were compared to their nearest neighbour. To examine the differences in grass biomass across distance in a given year, we used a subset of 44 sites situated along a continuous oval of roads Gobabeb–Mirabib–Ganab–Vogelfederberg–Gobabeb (Fig. 1). To avoid re-sampling when comparing all sites, comparisons were made only in one direction half-way around the oval. Each site was compared with the first 22 sites in an anti-clockwise direction, with the minimum distance between sites being 5 km and maximum 110 km. Grass biomass from site (i) was subtracted from the next (i+1), then the next after (i+2) ... until the most distant site (i+22) was reached. Absolute differences were recorded and the mean difference for each distance calculated.

RESULTS

I. Biomass-cover relationship

Burke's (1997) visual index of grass cover was highly correlated ($r=0.96$, $p<0.01$, $n=60$) with categories of grass biomass (derived from height) (Table 2). We used the midpoint of the range of grass biomass to convert the cover index to biomass. The threshold for visual assessment of patchiness was at 67% CV for grass height at a site.

II. Rainfall-productivity relationship

Dry biomass of grass was significantly correlated with rainfall ($r^2=0.58$, $p=0.0025$, $n=12$) and the relationship was:

$$grass\ biomass = 0.5872 \times (rain - 10.93).$$

The mean grass biomass varied between years, being highest in the good rainfall year, 2000, and lowest in 2003, when biomass was only 4.5% of the amount recorded in 2000 (Fig. 2). There were eight sites at which no grass was ever recorded and four sites that had fresh grass every year. Across all 87 sites, the mean frequency of grass occurrence at a site was 4.7 ±SD 3.1 years.

III. Spatio-temporal variation

The distribution of grass productivity varied strongly across the study area and between years (Fig. 3). Mean biomass increased over 70-fold from west to east. The maximum biomass at sites in each zone was recorded during 2000, ranging from 2.8 $g{\cdot}m^{-2}$ in the coastal zone, to 30.5 $g{\cdot}m^{-2}$ in the east. Temporal variability, as indicated by the mean coefficient of variation of grass biomass at sites that fall into each zone, was extremely high, ranging from 279% in the

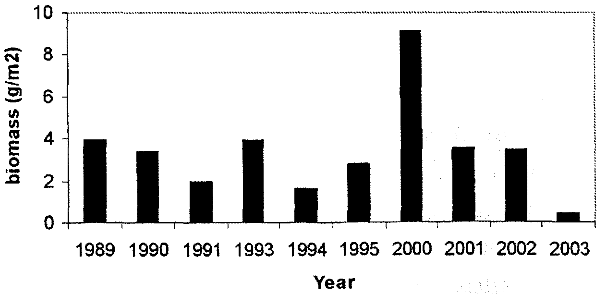

Fig. 2. Mean biomass of grass ($g{\cdot}m^{-2}$) at all sites over the entire study area in each year.

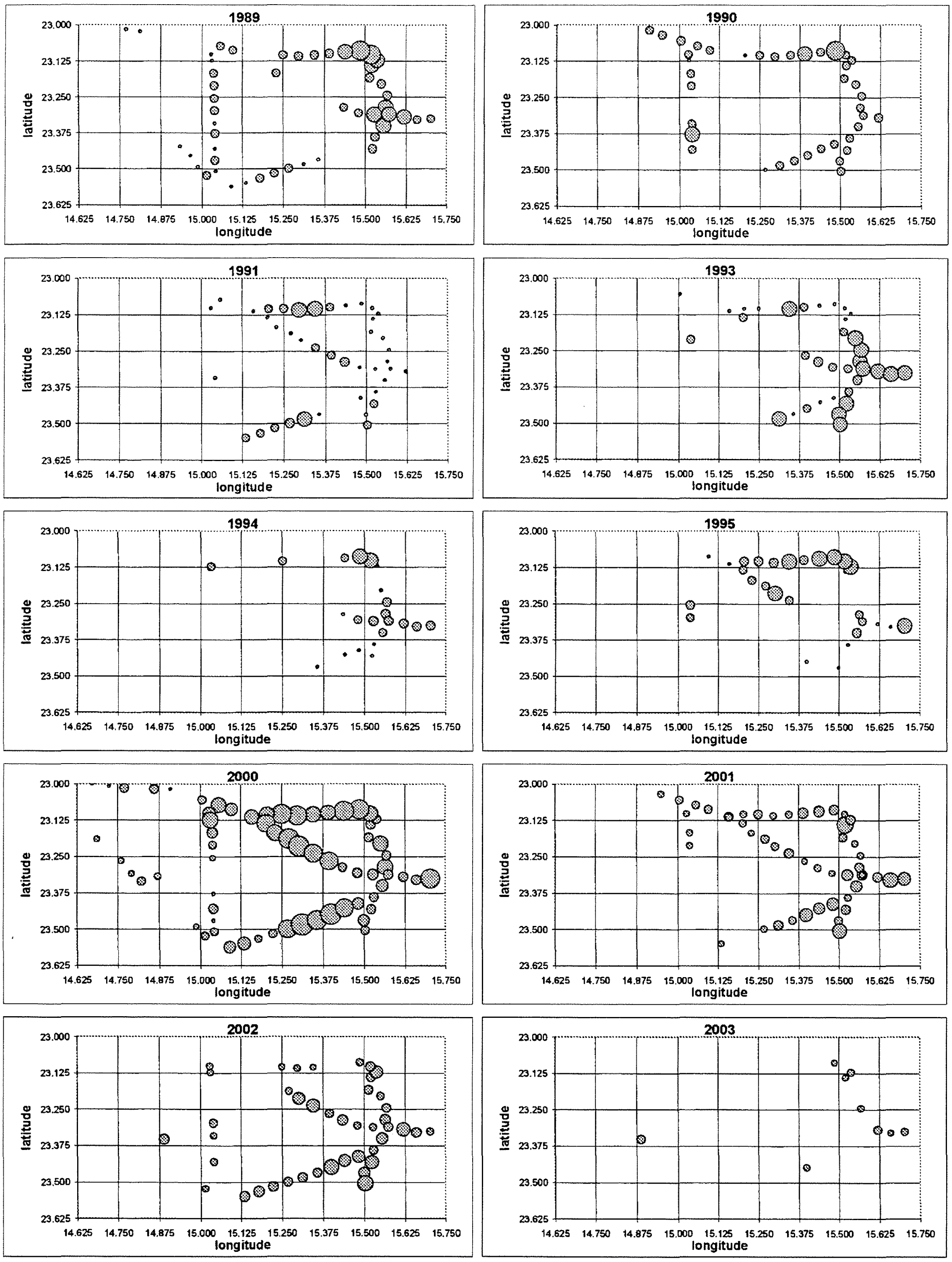

Fig. 3. Map of grass biomass in different years across the study area. Point size (area) is scaled to biomass ranging from 1 to 30 g·m^{-2}.

Table 3. Mean grass biomass (g·m^{-2}), mean coefficient of variation (%CV) and probability of grass per site in five zones of the Namib.

Zone	Sites	Biomass	CV	Probability of Grass (%)*
Coastal	12	0.085	279	4
Inland Fog	14	0.672	233	13
Transition	26	2.214	170	45
Middle	19	5.729	126	67
East Namib	16	6.108	86	86

* mean percent of number of years that a site in a zone had fresh grass

coastal zone to 86% in the eastern Namib (Table 3). During the 10 years of recording, the number of years with fresh grass at a site ranged from 0–1 in the coastal zone, to 7–10 in the eastern Namib, and the probability of effective rainfall occurring at a site in a given year increased over 20-fold from west to east (Table 3).

IV. Spatial scale

Within a given season, differences in grass biomass between adjacent sites (5 km apart) were smaller than between more distant sites. At the distance of 5 km, the difference was 50% of the difference in biomass that is reached at the asymptote distance of 50–80 km (Fig. 4). Differences continued to increase steeply at distances of 10–20 km, and then the rate of difference declined to the plateau level (Fig. 4).

The size of the area of greatest similarity differed little between years. Beyond 5 km distance the shapes of the curves differed, but in all cases its slope declined beyond 15–20 km, which was a second radius of similarity.

The spatial pattern of difference between adjacent sites was independent of the amplitude of grass biomass. There was no relationship between the overall grass biomass in the area in a given year (indicative of the extent of rainfall in the season) and the degree of similarity of sites 5 km apart (r^2=.074, p>0.05). In 2000, an exceptionally wet year, the first radius of similarity (50% difference) was 5 km and the second radius 20 km (change in slope) (Fig. 4), indicating that even when grass is most widespread, spatial variability still occurs at a similar spatial scale as in drier years.

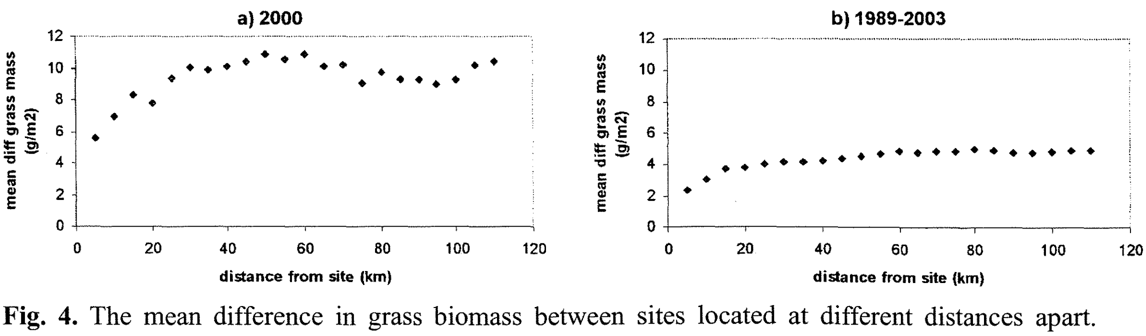

Fig. 4. The mean difference in grass biomass between sites located at different distances apart.

DISCUSSION

I. Biomass-cover relationship

Plant biomass measurements based on harvesting techniques provide a more accurate measure of productivity than estimates of plant cover (Kent & Coker, 1992). However, based on one year of data, this study showed a highly significant correlation between these two measures, indicating that plant cover estimates, if calibrated and done by the same person(s), can provide a reasonable surrogate for productivity. Taking the high temporal variability into account this relationship should, however, be tested in a less favourable season than 2000, in order to establish that this correlation also holds during normal to below average seasons. The use of cover estimates versus biomass measurements results in enormous savings in time and expense. In areas where little research funding is available for long-term studies, use of cover estimates may make such monitoring possible.

II. Rainfall-productivity relationship

Seely (1978a, 1978b) determined a relationship of grass standing crop to annual rainfall:

$$grass\ biomass = 0.5476 \times (rain - 11.30)$$

The study site used by Seely (1978a, 1978b) in 1974 fell into our own study area, and we found a very similar relationship during 2000 with a much smaller sample size than Seely's.

Our study also agrees with the zero intercept of grass germination in the order of 11 mm rainfall within a period of a week found in other empirical studies in the Central Namib Desert (Jacobson, 1992, 1997; Günster, 1992). This validates the Seely (1978a, 1978b) equation, at least for the desert end of the curve with annual rainfall less than 100 mm, where annual grass dominates. Given that perennial grasses are rare on the open gravel plains of the Central Namib, productivity here should only be related to the rainfall of a particular season and it would be invalid to apply average annual rainfall as is done in areas of higher rainfall (Rutherford, 1980; Ward & Ngairorue, 2000). Conversely, grass biomass in the Namib is indicative of the quantity of rainfall at a site within the range 11–100 mm, although at the upper half of that range in the Namib, nutrient availability becomes a limiting factor (Louw, 1990).

III. Spatio-temporal variation

Total grass productivity across the entire study area varied by more than an order of magnitude, reflecting conditions of extreme temporal variability across the Namib (Fig. 3). The pattern in this variability was that it decreased with increasing annual rainfall from west to east across the study area. In North

American deserts, not only regional rainfall gradients, but also particular storm paths, induced by topography, can be observed (Beatley, 1974). The possible effect of storm paths was initially also indicated during the first three years of study of Central Namib plains (Günster, 1995), but not maintained when longer-term data were included (Fig. 3).

Temporal variability was extremely high and a trend of decreasing variability from the coast to the inland areas was indicated, closely following the west-east gradient of variation in annual rainfall (Mendelsohn *et al.*, 2002). This confirms that rain events that can trigger development of grass only occur about once in a decade in the extreme arid coastal areas.

Changes in spatial and temporal variability of productivity in arid areas are expected as a result of climate change. This would particularly affect areas at the interface of grassland and shrubland (Huenneke *et al.*, 2002). Livestock grazing will exacerbate these effects (Huenneke *et al.*, 2002) and the Central Namib plains, which are free of livestock impacts, may be extremely important study areas in future to monitor changes and separate the effects of climate change from those of overgrazing.

In arid environments temporal changes need to be investigated over long time spans to generate meaningful results. This was also confirmed in this study when trends detected in the first three years of surveys (Günster, 1995) were re-analysed using six years of data (Burke, 1997), and now again with ten years of data.

IV. Spatial scale

The 5 km distance from a site where grass biomass was about 50% different to that site indicates that the scale of rainfall-induced variability in productivity has a radius of 5 km or less (a more exact estimate is limited at the current level of resolution). This is approximately the width of a cumulus cloud (Sharon, 1972, 1981). This area appears to be bigger when it is crossed obliquely, which may explain the secondary spatial scale of 15–20 km in our measurements.

No two study sites had exactly the same pattern of productivity over the years, except for several sites in the extreme north-west of the study area where only one or no rainfall events occurred (Fig. 3). Since the minimum scale of our study was 5 km (distance between adjacent study sites), this indicates that the observed spatial scale of individual rain clouds that have a radius of about 5 km determine the spatial pattern of productivity over the season. Even in wet years, idiosyncrasies of rain clouds determine the overall pattern, which is thus essentially random and unpredictable. Ward *et al.* (2004) reached a similar conclusion when comparing arid rangelands in Namibia, where productivity of annual and perennial grass is not only affected by rainfall, but also by livestock. In our case, the entire study area has the same type of land use (national park frequented by sparse herds of grazers), and differences can essentially be attributed to rainfall.

CONCLUSIONS

This study (1) indicated a good correlation between rapid grass cover assessments and more elaborate biomass harvesting techniques (2) confirmed a previously established relationship between rainfall and productivity, (3) illustrated extreme spatial variability of grass productivity at the regional scale on the Central Namib plains, (4) showed within-patch variability which is likely related to the extent of rain clouds.

By elucidating the implications of extreme temporal and spatial heterogeneity over long periods of time, desert ecology can advise the interpretation of biodiversity in heterogeneous environments in general. One implication is that the hydrological status of even nearby areas will usually be quite different, which could be a kind of virtual portioning of habitats. Primary productivity varies across a scale of 5–10 km and even nearby sites will have different patterns across a sequence of years. So, for instance, populations of detritivores would experience different conditions of food availability across a relatively small scale, which could give rise to different demographic statuses at this spatial scale.

The understanding of spatio-temporal patterns is important for comparing environmental changes induced by climate versus humans. Arid regions, such as Namibia, are particularly vulnerable to anthropogenic disturbance leading to high proportional loss of productivity. In view of this, it is very important to understand the consequences of variability in drylands (Henschel *et al.*, 2000). We recommend that long-term monitoring be continued in undisturbed areas for comparison that will improve interpretation of data from rangelands.

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ORIGIN OF THE FOG IN NAMIB DESERT IN DRY SEASON

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ABSTRACT The origin of the fog in the Namib Desert was generally considered the westerly advection fog over the Benguela cold current. When the author went to the Namib Desert in dry seasons in 2003 and 2004, the fog in the early morning, however, moved easterly from the inland to the Atlantic Ocean. It was the opposite direction of so called the sea fog. In addition to that, the fog in the Namib Desert showed the diurnal change: the fog arises in the early morning and disappeared before noon. The fog was usually driven easterly to the Atlantic Ocean. Through the climatic observation, the following were found for consideration of the origin of the fog on early August, 2004: it is not advection fog but that it is radiation fog. In the daytime, the air which is comparatively moist because of sea breeze moved to the inland, and it is solidified by radiative cooling in the night. Thus, the water vapor runs the fog and it is blown by the land wind to the westward.

Key Words: Radiation fog; Advection fog; Namib Desert; Diurnal change; Observation.

INTRODUCTION

The Namib Desert of which width is about 140 km expands along the west of Atlantic Ocean shore in Namibia. The origin of the fog over Namib Desert is considered the advection fog by the drifting of warm westerly wind over Benguela cold current which flows from the south in the Atlantic Ocean northward.

The process of the fog around the Namib Desert is generally considered a cooling process of air being saturated with moisture from the sea. For example, Mendlesohn *et al.* (2002) describes the process in three steps: in the first phase, the cold Benguela waters cool the air to such a degree that the moisture condenses into fog and low-level clouds offshore; secondly, low desert temperatures cause moist air that has come onshore on calm nights, to condense; and, finally, air may cool sufficiently to form fog when it is pushed upwards as it moves across the Namib Desert to higher elevations.

When the observation was carried out in Swakopmund, it was confirmed, however, that the fog arises between dawn and morning as diurnal change, and the easterly wind from the inland was frequent. Sea fog arises by pressure distribution and the generation time was not constant, generally. The fog is advected in the direction to the land from the sea. The fog observed near Swakopmund did not satisfy these features, instead, they show the diurnal change. The fog arises from early morning to before noon, and the fog is advected from the inland to the seaward. The features are clearly different from what has been explained as the sea fog until now.

As a detailed summary for understanding about fog, Sawai (1982) is often referred. In this explanation, the fog was divided into six types: slope fog, mixing fog, radiation fog, advection fog, steam fog and frontal fog. In Sawai (1982), sea fog was not classified as a type of fog but it was considered as advection fog or steam fog. Zhao *et al.* (1997) analyzed the sea fog around Yellow Sea and East China Sea with atmospheric and oceanic conditions.

In Japan, Kushiro city, which is a northern city of Japan, is famous for sea fog. There are a lot of studies about sea fog at Kushiro. For example, Ueda and Yagi (1984a, 1984b), Magono (1985), Sea fog research group (1985) and Sawai (1988) observed the sea fog around Kushiro, and its distribution, movements and vertical structure in detail. They found that the prediction of the sea fog was difficult.

On the other hand, sea fog can be captured by remotely sensed images. For example, the fog in Huang Hai Sea near China was analyzed by Kikukawa *et al.* (2002) by remote sensing methods.

In Namibia, the fog in the Namib Desert was considered the important source of water for plants and animals. Lancaster *et al.* (1994) observed the fog along Kuiseb River. Barnard (1998) pointed out that vegetation in the Namib Desert effectively uses the fog water. Henschel *et al.* (1998) and Syanyengana *et al.* (2002) examined the fog water, which was collected by mesh, was usable as drinking water for people.

This paper reexamines the origin of the fog which occurs in the Namib Desert through a survey. The purpose of this research is to detect the origin and the process of the fog formed in the Namib Desert. Especially, it analyzes the origin of the fog observed around Swakopmund on the west coast in early August, 2004, and clarifies the cause of generation.

STUDY AREA

The Namib Desert of which width is about 140 km expands along the west of Atlantic Ocean shore in Namibia. The observation of the fog was carried out near Swakopmund (Fig. 1). The climate in Swakopmund is mild throughout a year, and many tourists visit the city and many old people are spending the rest of their lives.

The mild climate is mainly produced by the Benguela cold current. Air temperature rises as it goes to inland from the seashore.

DATA AND OBSERVATION METHOD

In this research, the climate observation was carried out from August 7 to August 10, 2004 around Swakopmund. Fog occurred, daily at dawn, for these four days in the western Namib Desert around Swakopmund and its inland. Namibian Meteorological Service carries out the weather observation and Rus-

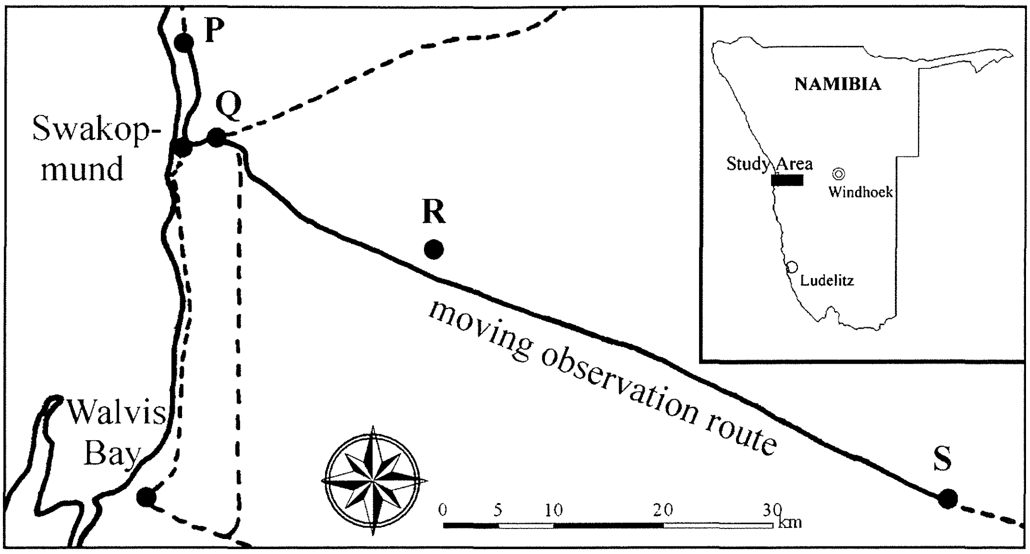

Fig. 1. Study area and observation points

sian weather data center (Hydro Met Center of Russian Federation & Satellite Monitoring Technologies Department of Space Research Institute, 2005) has opened the weather data to public. There are, however, only a few observation sites along the coast in Namibia. There is no weather observation site in Swakopmund. In Walvis Bay, which is 30 km south of Swakopmund, there is a weather observation site, but no data is currently exhibited in every 6 hours. Then the weather data in Ludelitz is used. Although Ludelitz is a little far from Swakopmund, the feature of being in the Namibian western coast is common, and the data in every 6 hours in an observation period is exhibited by the Russian weather data center.

Our weather observation was carried out from August 7 to August 10 near Swakopmund. The moving observation by car is shown at Fig. 1. We observed temperature and relative humidity every 30 seconds with the thermometer and hygrometer (TR-72S by TandD Co. Ltd.).

Also we carried out the vertical observation with a kite (the Delta Conyne Spectrum by New Tech Kite Co. Ltd.), a handy GPS (the eTrex Vista by Garmin Co. Ltd.) as altimeter, and the thermometer and hygrometer (TR-72S by TandD Co. Ltd.) at the points P and R shown at Fig. 1. All observation was recorded every 30 seconds. The total weight of the GPS and the thermometer and hygrometer was about 300 g. When the wind blew over about 3 m/s, the kite and the instruments were flied. And when the strong wind blew over 10 m/s, we needed very strong power to recover down. So the vertical observation was held when the wind blew between 3 m/s and 10 m/s.

OBSERVATION RESULTS

The fog in Swakopmund was observed every morning from August 7 to 10,

Table 1. Weather data at Ludelitz from August 7 to August 10, 2004 by Namibian Meteorological Agency.

Date	Time	Wind Direction (degree)	Wind Speed (m/s)	Temperature (°C)
August 7	1:00	140	6	9.0
	7:00	160	2	6.7
	13:00	200	9	17.7
	19:00	170	6	11.0
August 8	1:00	170	6	9.1
	7:00	110	3	6.7
	13:00	190	8	20.0
	19:00	190	5	11.8
August 9	1:00	170	7	10.0
	7:00	100	1	8.6
	13:00	190	11	18.4
	19:00	180	8	14.5
August 10	1:00	180	4	10.9
	7:00	70	1	8.6
	13:00	180	7	22.3
	19:00	180	5	11.9

: this mark is easterly breeze

2004. The fog could not be seen in Swakopmund Town along the sea shore in the morning on August 7 and 8. But the fog was found from the point Q (the junction B2-Road and C28-Road) in the inland side.

The wind data at Ludelitz from August 7 to August 10, 2004 was shown at Table 1. We also observed wind direction wind velocity which tended to be equal. Along the sea shore in Namibia, the wind at 7:00 (Namibian Local Time) was easterly every day, and the wind at other time was almost south-westerly. This is a diurnal wind change as land-sea breeze. The pressure system around Namibia was under the anticyclone area.

Our moving observation was carried out every morning for these four days. The observation course was shown in Fig. 1. The observation started at about 7:30 in the morning, and finished before noon as the fog disappeared.

The result of our moving observation of temperature from 9:27 to 10:30 on August 8, 2004 is shown in Fig. 2. Temperature is rising from the seashore toward inland. It can be classified into four zones, A to D, towards inland from near the seashore. The zone A is fluctuating in 2 °C first. Since this is near from the seashore, it is for the air current from the sea that tend to enter. Next, although the increasing rate of temperature of the zone B is small, temperature is rising gradually. A possible account is that a wind is weak and cooled down air during the night, as well as fog that occured in down, are still remaining. The rapid increase of temperature is seen at the zone C. This is because the hot and dry air mass from the inland pushes the fog to westward. In the zone D of the inland side, the temperature is reaching the ceiling. This is because

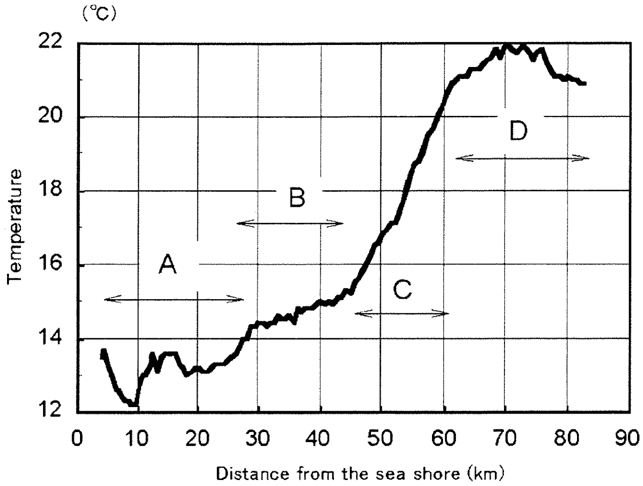

Fig. 2. Temperature distribution from the sea shore into the inland (from 9:27 to 10:30, August 8, 2004). A: The zone where the influence from the Atlantic Ocean is large. B: The zone where temperature rises loose. C: The zone where temperature rises rapid. D: The zone where the influence from the inland is large.

the air mass in this area is hardly influenced by the Atlantic Ocean. The boundary of the B zone and the C zone moves to east and west by time, but other boundaries do not move so much.

Although moving observation showed that air mass along the shore is cold and wet, and the air mass in inland is warm and superficially dry, in order to know the vertical distribution at point R (S22° 42' 24", E14° 36' 11") located in B zone, observation using the kite was performed. Vertical observation of temperature and humidity was performed in the morning and the afternoon of the same day (August 8, 2004), and the difference in air mass was investigated by water vapor in the air. This is done under consideration that relative humidity changes with temperature. Therefore, by setting the amount of moisture in 1 m^3 air mass as an index, we can explain the difference of air mass. The characteristics of the air mass in the morning and in the afternoon are different as this observation result was shown in Fig. 3. That is, air mass in the morning was wet and dry air mass had covered this area in the afternoon.

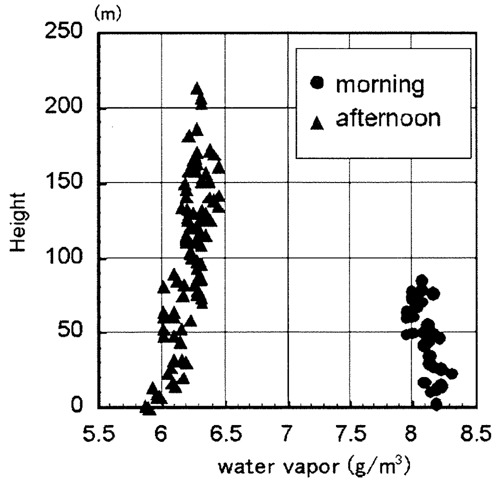

Fig. 3. The vertical distribution of the absolute humidity by the observation using a kite.
(S22° 42' 24", E14° 36' 11", Altitude: 90 m)
Morning: 8:26–8:50, August 8, 2004.
Afternoon: 12:05–13:00, August 8, 2004.

Thus, the origin of the fog in the Namib Desert was found in Fig. 3. In daytime, the wet air mass flows from seashore into inland about 60 km. After dawn, the radiative cooling occurs in the calm wind, and the water vapor is solidified. Since there are few amounts of water vapor, fog does not occur, but fog is washed away from east to west by easterly wind. Then, the sun rises in the morning, temperature rises from inland by sunshine, dry warm air reaches to near the seashore, and fog disappears.

TIME CHANGE AND VERTICAL STRUCTURE OF AIR MASS

When the amount of water vapor is an index of the air mass, the air mass of the inside of fog is different from that of the upper layer of the fog, and the misty upper end forms the small-scale front. And the upper air mass over fog is the almost same air mass as that of the inland where fog has not been generated.

A RELATION BETWEEN WIND DIRECTION AND WIND VELOCITY

Easterly wind was blowing in the morning when fog had occurred in the western coast in Namibia. This is considered land breeze in diurnal cycle. Moreover, the westerly or southern-westerly wind was blowing in daytime and it is thought that the water vapor from the sea had entered inner land by this wind. The wind direction and velocity in Table 1 suggests the distance that the water vapor from the sea runs into 60 km from the seashore, and this result has proven our moving observation.

WATER VAPOR ORIGIN AND ITS DIURNAL MOVING MECHANIZM IN THE NAMIB DESERT

As shown by the foregoing paragraph, when fog occurred in the Namib Desert in dry season, it turned out that not a sea breeze but land breeze is blowing. Moreover, it turned out that the sea breeze is blowing the daytime when fog has not occurred. Taking this fact into account, a hypothetical model is shown in Fig. 4. That is, the water vapor conveyed by the sea breeze to inland at daytime solidifies the fog in Namib Desert by radiative cooling at night, and radiation fog generates in inland. At this time, the distance into which the sea breeze which contains moisture at daytime can enter to inland is considered to be 60 km from the seashore. Simultaneously, it is washed away more into the direction to the Atlantic Ocean by the easterly land breeze because the radiation fog was formed by strong radiative cooling at night in desert. Under this mechanism, since temperature rises gradually as the sun rises, fog disappears and moves in the direction of the seashore. And in the daytime, sea breeze blows again and it will be the origin of the fog next day.

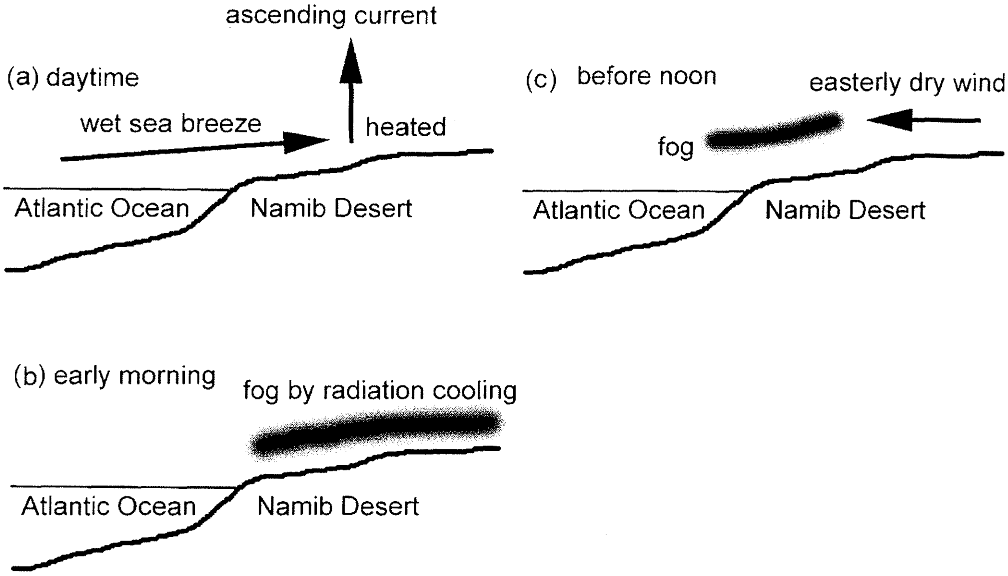

Fig. 4. The fog generating model in the Atlantic coast of Namibia in dry season.
(a) Daytime: The sun heated desert and the ascending current arises. The wet sea breeze flows from the west.
(b) Early morning: The radiative cooling occurs over the desert, the water vapor condenses, and then, the radiative fog occurs.
(c) Before noon: The dry land breeze blows from east, and the fog moves westward. The temperature over the inland arises.

CONCLUSION

The conventional understanding of the fog around the Namib Desert is that it is advection fog which is brought about by the warm westerly wind over the Benguela cold current from south to north. The wind direction and velocity data by the Namibia weather office, our moving observation of temperature and relative humidity by car, and our vertical observation, however, showed that the diurnal fog in dry season in the Namib Desert was radiation fog. Our observation is the result of being based on a field survey in the only dry season of Namibia, and the fog at other seasons has not been considered. Further observation to clarify the mechanism of the fog in Namib Desert at other seasons is required.

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CHANGES IN THE DISTRIBUTION OF THE !NARA PLANT THAT AFFECT THE LIFE OF THE TOPNAAR PEOPLE IN THE LOWER KUISEB RIVER, NAMIB DESERT

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ABSTRACT The !Nara plant is endemic to the central Namib Desert. The Topnaar people, who live along the Kuiseb River, use this plant in their daily lives, as it serves as a vital source of income, nutrition, and traditional culture. !Nara is virtually the only food source of the Topnaar during harvest time, and cash can be obtained by selling the seeds of the !Nara fruit. In fact, 40% of Topnaar harvesters have no other source of income. A flood protection wall was built in 1961 to protect Walvis Bay from flood damage, and a tributary that once flowed to the town was dammed as a result. A large percentage of !Nara was killed, and the crop yield decreased dramatically. The loss of floodwaters following the construction of the wall likely resulted in a decreased moisture supply, causing !Nara vegetation to suffer. It is probably difficult for seeds to germinate owing to increased erosion caused by flooding, the increased accumulation of sand, and the lowered groundwater table.

Key Words: !Nara; Topnaar; Namib Desert; Flood; Groundwater.

INTRODUCTION

Namibia is located in southwestern Africa and has an arid climate (Fig. 1). The Namib Desert, which is characterized by a desert climate, extends along the Atlantic coast. The Kuiseb is an ephemeral river that flows from the central region of the Namib Desert to the Atlantic Ocean and forms the Kuiseb delta. A unique plant, the !Nara (The '!' is an original click sound of Nama.) (*Acanthosicyos horridus*) (Fig. 2), is endemic to this area.

The Topnaar people who inhabit this region have long used the !Nara as a source of food and income (Seely, 1973; Budak, 1977; Shilomboleni, 1998), and depend heavily on it for sustenance. However, the conditions for !Nara growth have deteriorated, and crop yields have decreased in recent years (Shilomboleni, 1998). The cause of this deterioration remains unclear, as does the extent of its influence on the life of the Topnaar.

Although a detailed description of !Nara use is unavailable, several researchers have studied the use of this plant by the Topnaar (Ross, 1971; Budak, 1977; Dentlinger, 1977). Archeological research (Berry, 1991) and ecological studies (Kilopateck & Stock, 1994; Moser, 2001) have not revealed evidence of a similar decline in !Nara growth.

In this study, I examined the relationship between the !Nara plant and the Topnaar people, the influence of !Nara crop deterioration, and the cause of the crop decline. First, the use of !Nara by the Topnaar is discussed in detail, with

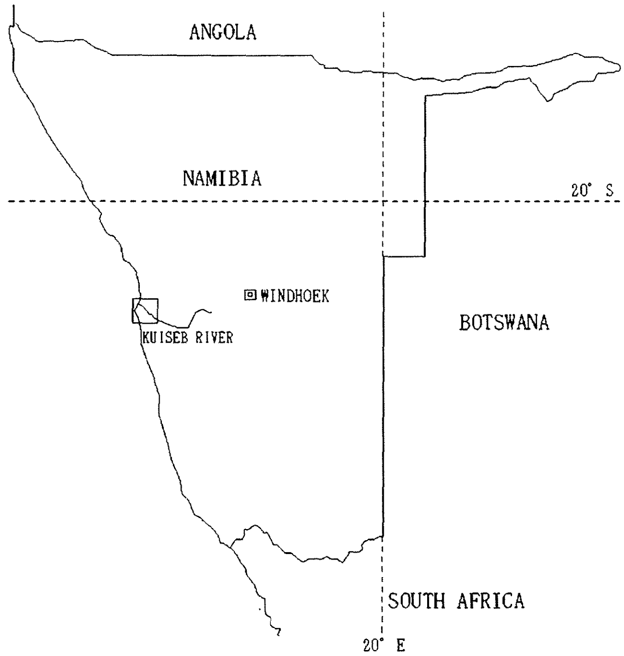

Fig. 1. Location of Namibia and Kuiseb River.

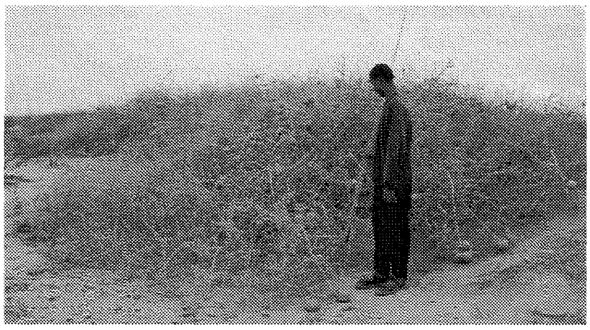

Fig. 2. !Nara (*Acanthosicyos horridus*).

particular attention given to changes in the lives of people and in the !Nara crop. Next, the social and ecological background of the decrease in crop yields is analyzed. Finally, the current situation facing the Topnaar and their future prospects are examined.

OUTLINE OF THE STUDY AREA

I. Namib Desert

The Namib Desert is one of the oldest deserts in the world (Seely, 1976; Ward, 1984). Namib is a Nama word that means "vast, dry land." This desert stretches about 140 km from east to west and about 2,000 km from south to north, from the northern part of the Republic of South Africa, across Angola, and to the coast of Namibia. The total area of the Namib Desert exceeds

140,000 square kilometers, and it borders the Atlantic Ocean for much of its length. A part of the Namib Desert is set aside as the Namib National Park, the fourth largest national park in the world.

The Namib Desert is a coastal desert that formed only within about 80–140 km of the Atlantic coast. The cold Benguela Current, which flows north from Antarctica, cools the coastal waters, forming a stratification of warm and cold atmospheric layers, thereby impeding the atmospheric circulation necessary for the formation of rain clouds. As a result, the coastline experiences an extremely dry climate, with an average precipitation of 15 mm per year. In contrast, the eastern side of the desert receives an average yearly precipitation of about 100 mm, owing to the waning influence of the Benguela Current. However, as there are some regions in which precipitation has not been recorded at all during the past 20 years (Seely, 1976), the Namib Desert is considered one of the driest regions in the world.

Despite these low levels of precipitation, fog generation is widespread throughout the coastal region of the Namib Desert. Cold air from the sea cools the warm air over the land in a process similar to that of rain cloud development, and the fog rises. Moving inland from the coast, the dominant southwesterly winds can carry the fog over 30 km in one morning. It is not unusual for the fog to travel 100 km or more from the coast. The fog generated by this process generally develops by sunrise, dissipates as the temperature rises, and often disappears entirely by noon. Fog, though ephemeral, is a valuable source of moisture in this harsh environment (Seely, 1976).

II. Kuiseb River valley and the study village

Walvis Bay is located 30 km north-west from the research area. The rain and temperature charts for Walvis Bay record a yearly rainfall of less than 10 mm and relatively low temperatures.

The combination of moisture from fog and from the Kuiseb River enables life to exist in this severe environment (Ross, 1971; Seely, 1976). The Kuiseb River collects water in the Khomas Highlands, where the average precipitation is 300–400 mm per year, and flows west toward the Atlantic Ocean through the central region of the Namib Desert. The Kuiseb River spans about 440 km and has two tributaries. One flows to the north, toward the city of Walvis Bay about 30 km from the coast, and the other flows to the west, directly to the Atlantic Ocean. During flooding, the Kuiseb River flushes the sand that has accumulated from the movement of the dunes and controls the north-to-south shifting of the dunes (Goudie, 1972).

Oases are generally found in the central part of the desert, where they supply valuable moisture to plants and animals. The Kuiseb River performs a similar role, forming an oasis not at isolated points, but as a line that stretches across the Namib Desert. *Faidherbia albida* and *Acacia erioloba* grow profusely along the riverbed and offer shade to the jackals and oryx that live in the Kuiseb River valley, and their leaves and pods provide food for the goats of the Topnaar.

Twelve Topnaar settlements lie within about 150 km east and west of the Kuiseb River, with a total population of about 500 people. This study was conducted in the village of Aramstrat, which includes 51 people. The village is close to the !Nara harvest area and is therefore a useful site for examining the relationship between the people and the !Nara plant.

ECOLOGY AND DISTRIBUTION OF THE !NARA PLANT IN THE KUISEB DELTA

I. Botany of !Nara

!Nara is a cucurbitaceous plant that is distributed primarily in the lower Kuiseb River, although it is also widely distributed along the coast of the southern part of Angola. During the 19th century, Friedrich Welwitsch established that !Nara is endemic to the area and has existed along the coast of Namibia since about 40 million years ago (Berry, 1991).

The multiple greenish branches of the !Nara plant are covered by thorns about 2–3 cm long, which conduct photosynthesis in lieu of leaves. The body of the plant is referred to as a "hummock" because it collects the sand around the stalk during its growth, forming a slightly elevated mound. One hummock may grow up to 1,500 m^2 or more (Klopateck & Stock, 1994).

The roots of a !Nara can extend 30 m deep to obtain moisture, and the plant also absorbs water from the fog that rises in the morning. Water is stored in the roots to prevent evaporation under the extremely arid conditions of the Namib Desert.

The fruit of the !Nara plant, the !Nara melon, is edible, and the cream-colored seeds are called butter nut. !Nara melon can grow to about 1 kg and 15–20 cm in diameter (Klopateck & Stock, 1994). Of 100 fruits harvested, each fruit had an average weight of 667 g, of which butter nut comprised 52.2 g. The !Nara melon contains a high percentage of moisture, and the butter nut is highly nutritious, with 32% protein and 46% oil (Pfeifer, 1979). This fruit sustains not only wild animals such as jackal, oryx, springbok, mice, and the !Nara beetle, but also the people who live in nearby areas (Pfeifer, 1979; Kilopateck & Stock, 1994).

II. Distribution region of !Nara in the Kuiseb delta

Fig. 3 shows the distribution of the !Nara plant in the Kuiseb delta. !Nara is distributed from the bend in the Kuiseb River to the coastline near the river. The region where !Nara is distributed, the !Nara fields, is characterized by vegetation that differs from that of the Kuiseb riverbed, especially with respect to acacia trees.

Sand accumulates in the !Nara fields as a result of flooding of the Kuiseb River, which contributes to the germination and growth of individual plants.

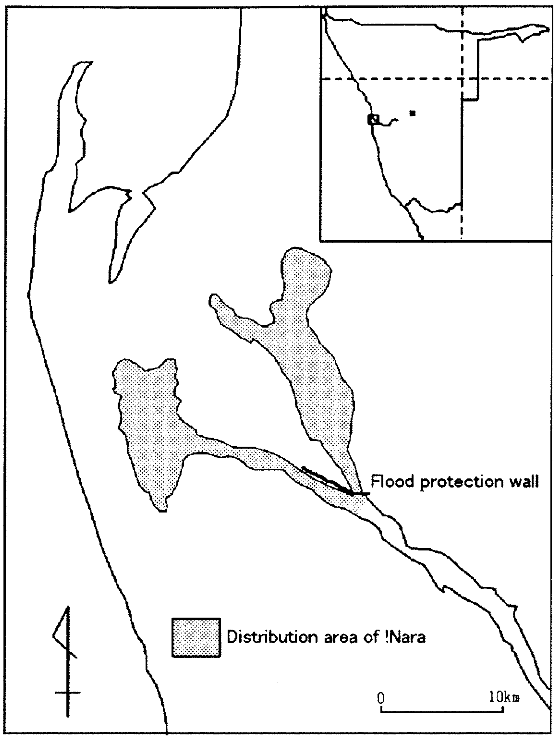

Fig. 3. Distribution of !Nara in the Kuiseb delta.

The moisture supplied to the soil is thought to favor the renewal of vegetation. Flooding is therefore thought to play a vital role in the growth of the !Nara plant.

TOPNAAR LIFE AND !NARA

I. History of the Topnaar as a Society and as an Economy

Topnaar is a part of the Nama branch of the Khoisan language group (Eynden, et al., 1992). The Topnaar, or #Aonin (The '#' is an original click sound of Nama, too.) in the Nama language, live in and around the lower Kuiseb River and Sesfontein area, stretching 500 km from Walvis Bay to the north (Budack, 1977). Some of the Topnaar people who had lived in the Sesfontein area migrated to the lower Kuiseb River region during the 14th century (Eynden, et al., 1992).

These people have historically been fishermen, goat-herders, and !Nara harvesters. Old records contain accounts of the Topnaar offering beef, goat meat, milk, water, and !Nara fruits to European trade ships in exchange for general merchandise, clothes, weapons, and alcohol.

The main occupations of the Topnaar are goat husbandry and !Nara cultivation. Harvesting is mostly undertaken by men, but women occasionally assist in the harvest when necessary. Goats are kept in every home, sometimes in great numbers, and are pastured in the Kuiseb riverbed during the daytime, returning to the village in the evening. The primary means of generating income for the Topnaar is by selling butter nuts and goat skins or through paid labor. Goat skins are taken to the city to be sold, while the meat is retained for private consumption.

A few people work in the nearby mines and towns such as Walvis Bay and Swakopmund. In Aramstrat, only one person worked in the town regularly, although some individuals worked temporary, seasonal jobs. Payment for work in the mines is low, usually only about N$100–150. However, because of the high unemployment rate in Namibia, there are many applicants for work. The government supplies a monthly pension to men and women over the age of 60, which is a vital source of income for the community, but the most important source of income for the Topnaar is the sale of !Nara butter nut. The money obtained is used to buy food, such as maize flour and salted cow bone, and to pay for medical and educational expenses.

II. Use of !Nara

Although !Nara bears fruit throughout the year, there are two primary harvesting periods. The first is the shorter harvesting season from August to September, and the longer season runs from late December to late March. Harvesters go to the !Nara fields either alone or with their families to collect !Nara fruits; on site, they live in small, simple huts.

The method of harvesting is quite simple. Workers poke the !Nara melons with long sticks, separating them from the branches. It is often difficult to distinguish if the fruit is ripe enough; generally, when the inside is orange, the fruit is ripe enough to harvest. Harvested !Nara melons are collected in a large drum and returned to the huts in donkey carts.

III. Eating Habits

A typical example of cooking with !Nara is the !Nara cake. !Nara fruit is boiled and stirred with a long stick in a large drum until it has been reduced to half its volume. The seeds are separated from the liquid during the boiling process and are extracted. The liquid is then dried on a sand dune or a plastic sheet for several days. !Nara cake is eaten alone or with cooked maize.

After the time-consuming work of removing the husks from the seeds, butter nuts that has been coated with sand are cooked in a pan until it is light brown, after which the sand is removed by rubbing it off by hand.

IV. Economic Activities

The cooked seeds are bagged and sold in town, after reserving some for the villagers. Cooked seeds can usually be stored for up to two years without spoiling. According to interviews with 25 !Nara harvesters, the amount of harvested !Nara averages about 490 kg per year per person, of which about 200 –250 kg are sold. Because the butter nut is sold for N$6–8 per kg, the average profit from the sale of butter nut is about N$1200–2000 per year. This income is very important to the Topnaar people, because 40% of the harvesters have no other source of income, and 43% of the average annual income is from selling seeds. The dependency of the Topnaar on the !Nara plant is clearly quite high.

INFLUENCE OF VEGETATION CHANGES ON !NARA

I. Vegetation Change and Its Causes

!Nara plants grow across a wide area of the Kuiseb delta. However, since a flood protection wall was constructed in 1961, the distribution of !Nara in the Kuiseb delta has been dramatically reduced. The flood protection wall, constructed by the South African government, protects the harbors of the city of Walvis Bay downstream from the Kuiseb River, which floods every 8 to 10 years.

Fig. 4 shows the distribution of !Nara in 1977. Sixteen years after the construction of the wall, !Nara were scattered and sparsely distributed both along the tributary and the main river. Aerial photography confirms the presence of vegetation such as bushes and herbs in 1977, but by 1997, !Nara along the tributary had disappeared and was observed only in the sand dunes. This may be owing to a lack of water flowing from the tributary, gradually retarding the growth of !Nara. According to one harvester, crops were plentiful and healthy throughout the 1980s, despite the existence of the protection wall, but diminished rapidly during the 1990s.

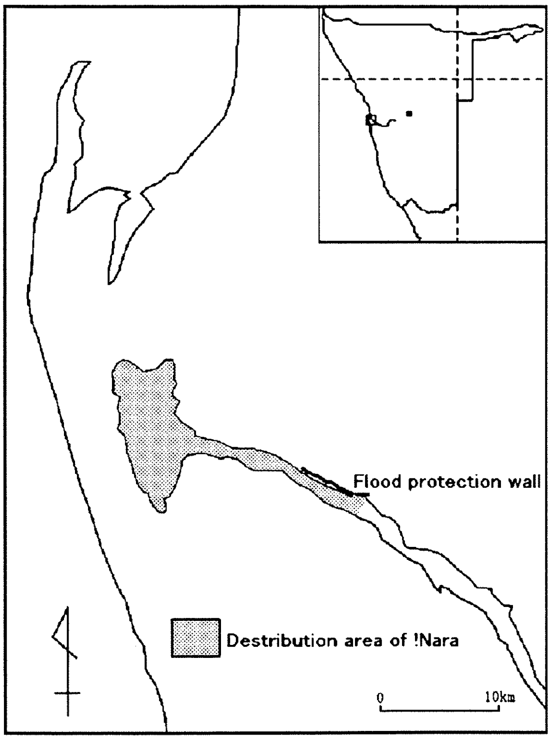

Fig. 4. Distribution area of !Nara in 1977.

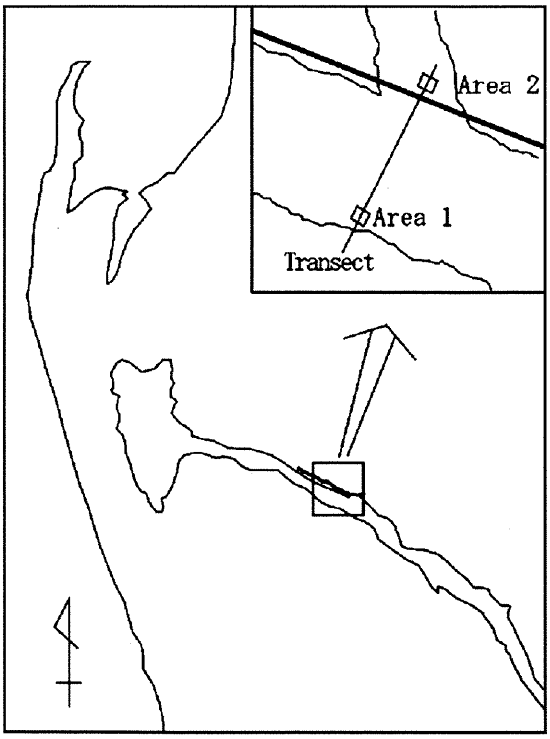

Fig. 5. Transect and cross-sectional area.

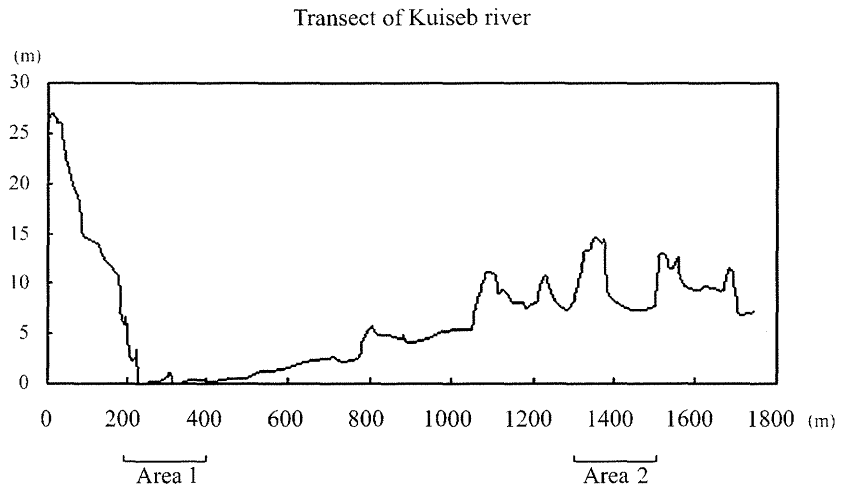

Fig. 6. Transect of Kuiseb River.

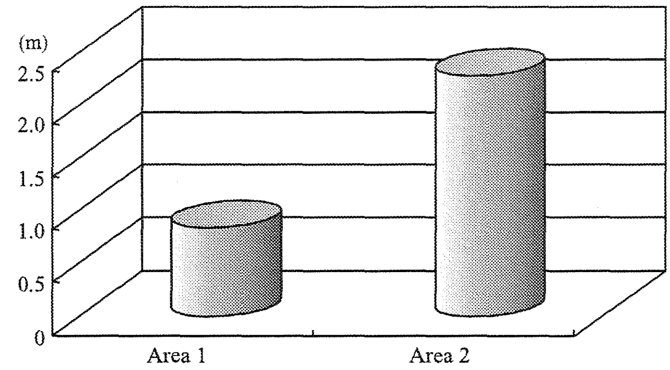

Fig. 7. Average height of one mound.

To examine this phenomenon, I tracked !Nara vegetation in the Kuiseb delta from the time of the construction of the wall through the next 40 years. The distribution of vegetation was investigated by taking a cross section of both the main river and the tributary, and then delineating surrounding areas of 200 × 200 m (Fig. 5). The area established in the primary branch of the Kuiseb River was labeled Area 1, and the area near the tributary was Area 2 (Fig 6). The auther recorded the area covered by each plant, the rate of withering of each plant, and height of each mound.

The mound heights of the plants in Area 2 were about three times higher than those of Area 1 (Fig. 7). This may be because water stopped flowing to the area after the construction of the wall, allowing the unimpeded build-up of sand. Additionally, the area covered by plants in Area 2, 115.8 m^2, exceeded that of Area 1, 46.2 m^2 (Fig. 8). Finally, the rate of individual plant withering (70%) of the plants in Area 2 was at least twice as much as that of in Area 1 (Fig. 9). It may be that older !Nara plants are usually replaced as flooding erodes the mounds and encourages new germination. However, this process would have ceased with the construction of the protection wall.

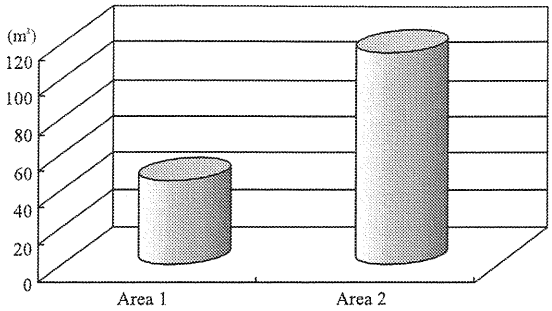

Fig. 8. Average area of one mound.

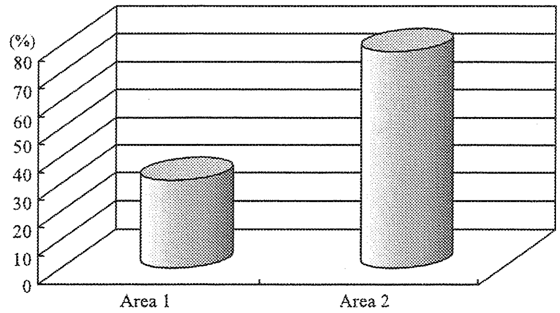

Fig. 9. Average death rate of one mound.

II. Floods and Germination

There are generally two methods by which plants adjust to the desert environment. The first method is to alter the plant structure to enable growth under more stressful conditions; the other is for the plant to enter dormancy to evade stress. The release of the seeds while a plant is dormant is usually induced by increased moisture in the desert. Sand must contain moisture for at least 4 days for the dormant release of the !Nara seed to occur (Moser, 2001). It therefore seems that seed germination is hindered in the tributary region because of a lack of sufficient water to induce dormant seed release.

III. Accumulation of Sand and Decreasing Underground Water Levels

A great deal of sand has accumulated in the area of the old riverbed, resulting in an increase in elevation of at least 10 m. This change makes it difficult, if not impossible, for young roots to reach the groundwater during the early stages of growth, increasing the difficulty of germination.

The growth rate of roots that germinate from seeds of the !Nara plant is far slower than that of many other plants growing in the desert (Moser, 2001). The seed roots of desert plants such as *Acacia nilotica* and *Mundulea sericea* grow at a rate of over 2 mm per day, but the !Nara seed root grows only 0.6 to 1.3 mm per day. Roots must grow as rapidly as possible to survive in the extremely dry environment of the desert. However, a major feature of the !Nara plant is this slow rate of growth (Moser, 2001). It is likely that many plants die before they can extend their roots to reach groundwater because of the arid conditions of the old riverbed.

The number of dams in the Kuiseb region has increased every year, from 152 dams in 1972 to 362 in 1997. These dams are constructed to meet the rise in demand for water in the cities. In addition, many pumps have been erected in the Kuiseb riverbed to extract more underground water to meet this demand.

Windhoek, the capital city of Namibia, lies upstream on the eastern side of the Kuiseb River. The rate of development in Windhoek has been remarkable, with a rapid increase in population that has brought with it an increase in the demand for water. Many of the dams in the Kuiseb River were constructed to meet this demand, and to secure the supply of water to the area.

The building of more dams and the use of groundwater have resulted in a marked decrease in the groundwater level. In the 1970s, the groundwater level at Rooibank was 2 to 4 m deep, fell to 8 m in 1988, and was recorded at 12.15 m in 1994. It is likely that the observed deterioration of !Nara plants in the region is owing to the accumulation of sand and the lowering of the groundwater table.

CONCLUSION

The Kuiseb delta contains the largest population of !Nara, and the Topnaar people are particularly dependent on the !Nara plant. Although this dependency has diminished over the last few decades, it is still vital to their survival. The life of the Topnaar will most certainly be jeopardized if the deterioration in the !Nara continues, and the harvest has already been reduced by half over the last 30 years.

The Kuiseb River experienced large-scale flooding 16 times over the past 160 years. However, in the last 50 years, only one large flood reached the Kuiseb delta. Instances of flood water reaching the !Nara fields are now quite rare.

Water from floods, the accumulation of sand, and the renewal of old plants are all necessary to the growth of !Nara. Owing to the construction of the flood protection wall in 1961, !Nara vegetation in the area has been nearly destroyed.

The decrease in flood water, lack of clearing of old !Nara plants, a decrease in reproduction, lack of dormant seed release, obstruction of germination, and an increased distance to groundwater owing to sand accumulation have all contributed to the decline in !Nara vegetation.

Many harvesters recognize that the crops are decreasing, but they lack a solution to the problem. Although crop deterioration has been confirmed only in the !Nara field near the tributary, the continued descent of the groundwater table, combined with a lack of flood water, will likely lead to further !Nara crop deterioration in the region of the main stream in the near future. Further study is required to investigate methods of improving the growth of !Nara, and to find solutions to the problems of the lowering groundwater table and the decrease in flooding.

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CHANGE IN POPULATION AND LAND-USE INTENSITIES IN SEVERAL VILLAGES OF THE FOUR NORTHERN REGIONS OF NAMIBIA

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ABSTRACT Demographic changes in several rural areas in the four northern regions of Namibia were traced from 1991 to 2001 using national census data. On average, the population growth rate of the surveyed area was 2.77% per year. Although this rate approximated the country's mean growth rate of 2.64%, the surveyed areas showed significant differences from the mean, ranging from -3.4% to 7.2% per year. A combination of demographic and land use data collected from four representative villages in the study region revealed that rural-to-urban migration on a micro-scale is a significant process in the control of the area's ecology and economy, and that the percentage of cultivated land is closely tied to population density.

Key Words: Namibia; Owamboland; Four northern regions; Population census; Land use intensity.

INTRODUCTION

Since gaining independence in 1990, Namibia has experienced drastic socio-economic changes, resulting in serious environmental changes that are of major concern to international organizations and the NGOs that assist rural development through combating desertification (Desert Research Foundation of Namibia, 1995). However, the assumption that a population increase induces environmental degradation through the overutilization of natural resources lacks substantial evidence in certain local situations, and may lead to misguided rural development strategies. In fact, increased population pressure does not always cause environmental degradation, nor does it necessarily lead to the breakdown of traditional agriculture. Rather, farmers play a crucial role in preventing this by adopting new agricultural strategies, according to changes in their environment. Mortimore (1998) showed that a population increase supported agricultural intensification, such as improved farm management and tree planting, in villages near Kano, Nigeria. In addition, the Akamba farmers of Machakos, Kenya, began to construct terraces that were introduced by the colonial government but these were later abolished (Mortimore, 1998). On the contrary, the environment can be degraded by other reasons than population increase such as the change in cropping patterns.

Demographic statistics demonstrate that the environment and livelihood of Owamboland, now known as the four northern regions of Namibia, are under threat on a regional scale (Mendelsohn *et al.,* 2000). This paper examines the relationship between population increase and environmental degradation in smaller areas, such as within a specific village, and tests quantitatively the idea that population pressure is a real cause of environmental degradation in the area.

RESEARCH AREA AND METHODOLOGY

I. Research Area

Several areas within the four northern regions (Omusati, Ohangwena, Oshana, and Oshikoto) were selected for demographic analysis and land use survey. Fig. 1 shows the location of the four northern regions in Namibia. These regions occupy 84,600 km^2 of the land surface of Namibia, or 9.7% of the country's land, and are populated by 780,000 people. The area is separated into three distinct sections: Owamboland, Etosha National Park, and the Tsumeb commercial farming area, with Owamboland comprising the northern 60%. Since the mid-sixteenth century, Owamboland has been the residential area of the Owambo people, whose chiefdoms extend to southern Angola. The Owambo grow pearl millet and graze cattle, assisted by a relatively high annual precipitation of more than 300 mm per year. The land is under the chief's control and is therefore considered communal land. Before gaining independence

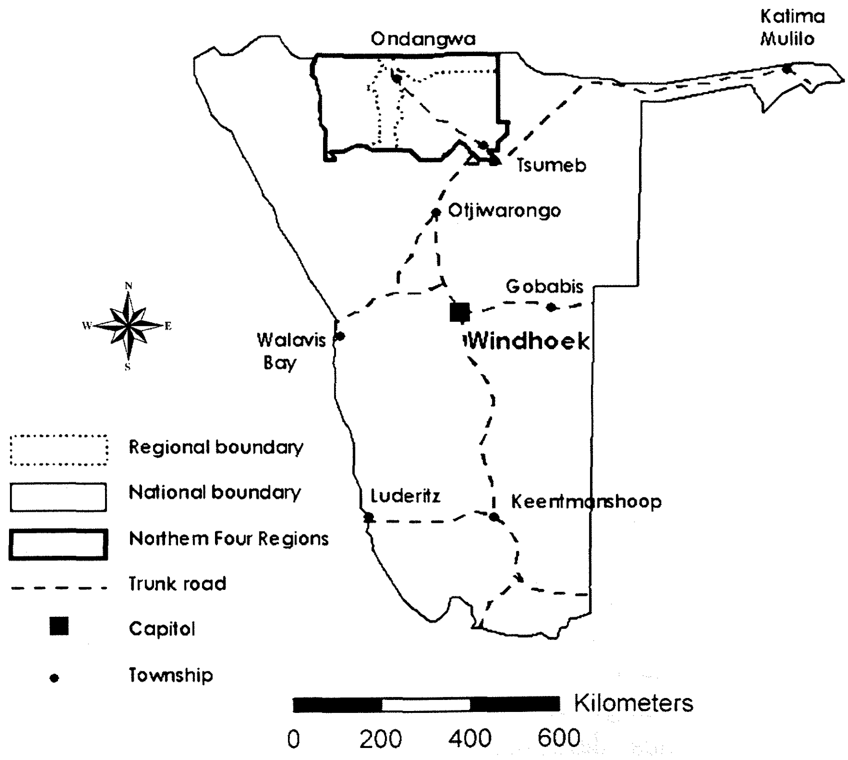

Fig. 1. Location of the four northern regions.

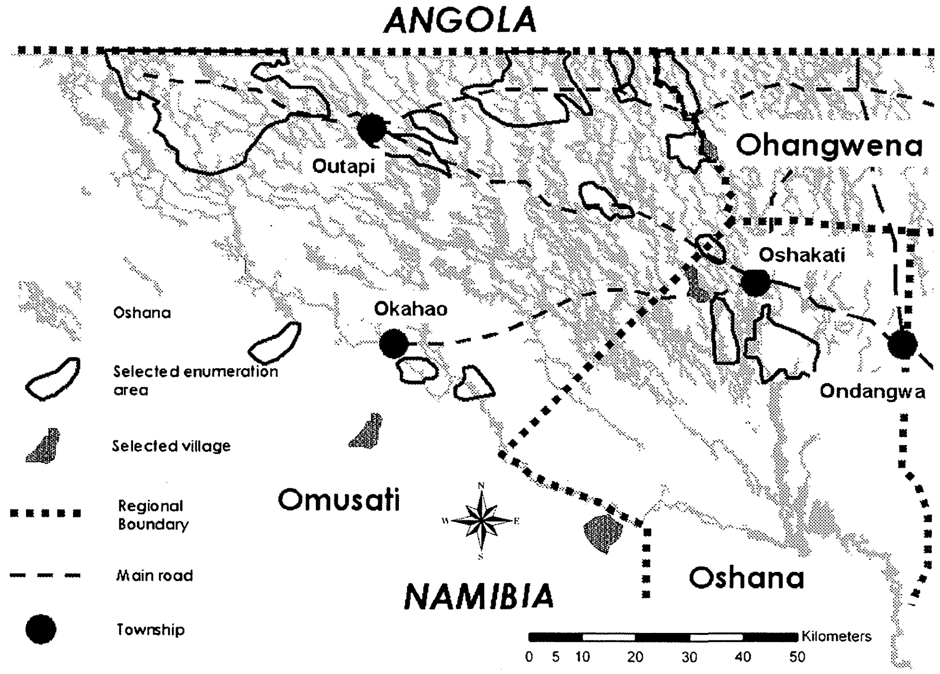

Fig. 2. Research area.

in 1990, the area was one of the homelands under the apartheid regime, and the migration of black people was strictly controlled at the border.

Fig. 2 shows the research area. This area includes part of the catchment area of the Cuvelai River, which collects water from Angola and drains into the Etosha Pan in the south, and is characterized by the domination of the 'oshana', which, in the Owambo language, refers to the drainage networks of seasonal floods. Although the oshana dries up during the dry season, it continues to supply groundwater, making it possible for the Owambo people to settle here permanently. As will be discussed later, population distribution in the area is strongly related to the presence of the oshana.

Outapi and Oshakati are the centers of the Omusati and Oshana regions, respectively, and are home to the regional government offices, whereas local government offices, a lower level of the administration, are located in Okahao and Ondangwa. Fig. 2 also shows the fifteen areas of enumeration used to analyze demographic changes between 1991 and 2001, and the four villages surveyed for current land use status.

The study area, which is about 1100 m above sea level, is topographically very flat, with some minor undulation caused by the oshana and the inter-fluvial hills, composed of Kalahari sand deposits. The vegetation of the area is characterized by a mosaic of grasslands and mopane shrubs, of which *Colophospermum mopane* is dominant (Mendelsohn *et al.,* 2000).

II. Collection of Demographic Data

The Office of the National Planning Commission provided the digitized national census data for the study areas from 1991 to 2001. These data sets were later combined using GIS software (ArcView), and were examined for changes in population density, and for the relationship between population density and land use. The major problem encountered in this analysis was that the enumeration units, at the lowest level that approximately coincided with the placement of villages, were, in many cases, inconsistent from 1991 to 2001, which made the direct comparison of demography at the lowest level very difficult. To overcome this discrepancy, images of the different enumeration units were superimposed, and composite data, both single and aggregate, were delineated in a series of polygons, as shown in Fig. 1. Although such direct comparison limits the quality of the analysis, because of the varying sizes of enumeration units, the method is valid if the results are interpreted carefully, taking such discrepancies into account.

III. Field Survey

Four villages were selected, based on their respective distances from the Oshakati township and their population densities. Approximately ten households in each village were interviewed regarding their family status, farming activities, and source of income. The area of each family's smallholding and the area of their pearl millet fields were measured using GPS.

IV. Satellite Image Analysis

The band 8 data of Landsat TM7 imaginary (path: 180, row: 72), recorded on June 22, 2002, were used to identify the spatial relationships between objects found during the field survey. The proportion of the oshana within a village was measured in the image, and the population density of each village was recalculated by excluding the oshana.

RESULTS AND DISCUSSION

I. Population Trends in Namibia from 1991 to 2001

As shown in Table. 1, the population of Namibia increased from 1.41 million to 1.83 million between 1991 and 2001, with an annual growth rate of 2.6%, while the population of the four northern regions increased from 0.63 million to 0.78 million, with an annual growth rate of 2.1% (Census Bureau of Statistics, 2003). In addition, the proportional population of the four northern regions decreased from 44.9% in 1991 to 42.6% in 2001. Urban-rural distribution showed more drastic changes during this period, as urban areas had a high annual rate of 4.7% population growth, in contrast to the 1.8% increase experienced in rural areas. This can be ascribed to the rural-to-urban migration of people, although the natural growth rates of both urban and rural areas

Table 1. Population trends in Namibia from 1991 to 2001.

	Population in 1991	Percent in 1991	Population in 2001	Percent in 2001	Growth rate per annum (%)
Whole country	1,409,920	100	1,830,330	100	2.6
Northern four regions	633,054	44.9	780,149	42.6	2.1
Urban areas	382,088	27.1	603,612	33.0	4.7
Rural areas	1,027,832	72.9	1,226,718	67.0	1.8

should also be taken into account.

The four northern regions are the most densely populated regions in Namibia. Forty-three percent of the population inhabit only 9.7% of the total land area, so that the population density of the four northern regions can reach 9.25 people/km^2, far exceeding the country average of 2.1 people/km^2. Although Namibia is the second most sparsely populated country in Africa after Western Sahara (United Nations, 2002), historical influences and climatic conditions conducive to sedentary agriculture contribute to the relatively high population of the four northern regions.

The current high population of the four northern regions operates as a strong motivator for migration to urban areas. The population of the Katutura area, a residential area of Windhoek for black people, increased from 19,000 in 1968 to 91,000 in 1991, with an attendant increase from 17% to 42% of Owambo people (Pendleton, 1997). Such rural-to-urban migration is not directed solely to the capital; it also affects the country's other urban areas, comprising eighteen municipalities and twelve towns nationwide (Mendelsohn, *et al.*, 2002).

According to United Nations predictions, 57% of the population of developing countries will be concentrated in urban areas by 2030, while the rural population of developing countries will reach a maximum of 3.3 billion, followed by a gradual decrease (United Nations Population Division, 2004). The population of Namibia may follow this trend, but the present high population density of the four northern regions will continue to be a strong motivator with respect to urban migration for years to come.

II. Population change by enumeration areas

The current population density of the research area is based on 2002 census data (Fig. 3). A comparison of Fig. 2 with Fig. 3 reveals that the three townships of Oshakati, Outapi, and Okahao overlap densely populated areas of more than 100 people/km^2. However, another area with high density in the rural area, indicated by the roman numeral II, is a part of central Owamboland that extends east toward the Ohangwena region. Fig. 3 also illustrates the vital role that oshana plays in residents' lives by providing water, fish, and favorable conditions for pearl millet cultivation. Such an uneven distribution of people requires further analysis from both an environmental and a socio-economic point of view. In addition, Fig. 3 shows the selected enumeration units for demographic analysis. There are fifteen blocks of sampled areas, which are

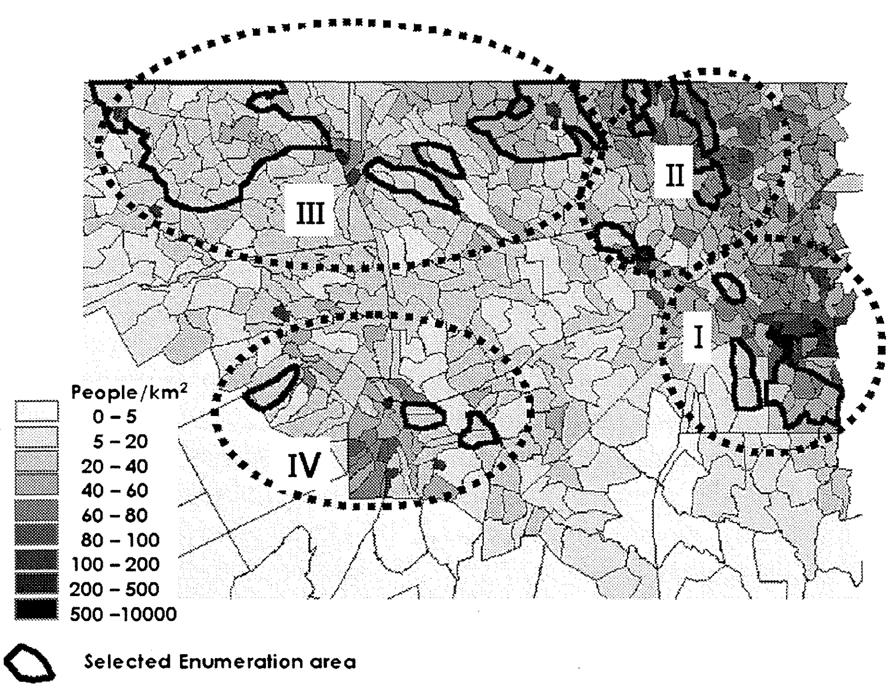

Fig. 3. Selected enumeration areas and population density in 2001.

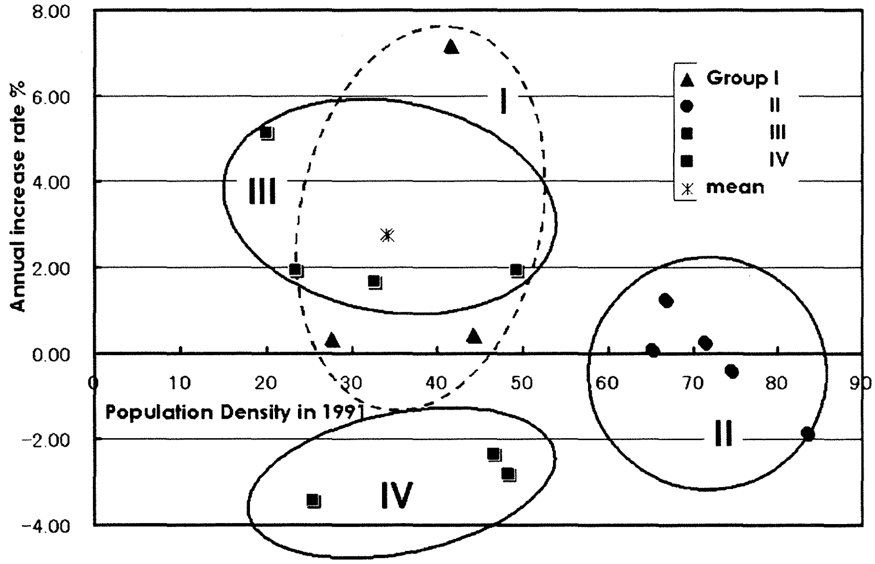

Fig. 4. Relationship between population growth rate and population density in 1991.

conveniently grouped into four classes (I–IV) according to their geographical distribution. Group I can be characterized as lying within the vicinity of Oshakati township, and Group II is a densely populated rural area. Groups III and IV are both distant from Oshakati township, but are closer to local government centers than Groups I and II. The annual population growth rate in each enumeration area from 1991 to 2001 was plotted against the population density of 1991 (Fig. 4). The average annual growth rate of all of the study areas, indicated by ∗, was 2.77%, which was close to the country's average rate of 2.64%. However, some enumeration areas experienced greater disparities in growth rates, ranging from -3.4% to 7.2%. Such divergences from the norm can be ascribed to the micro-scale movement of the population within the research area, along with out-migration to other regions. Group II exhibited a narrower range of population growth rate, with an average rate of nearly zero. This may be explained by the fact that Group II is a highly populated rural area, almost saturated with people, and the natural population increase has been forced away from the area, owing to the pressure of overpopulation. Group IV is characterized by a negative growth rate of between -2.8% to -3.4 %. A possible explanation for this could be that the population of Group IV has been absorbed into the nearby Okahao township. Groups I and III include enumeration areas with high growth rates. The 7.2% growth rate found in Group I might be owing to the expansion of Oshakati township. The high growth rate of 5.1%, seen in Group III, has no obvious explanation, although it may be because of some erratic population factors associated with the low population density of 1991.

Since the enumeration areas examined in this study do not include township areas, these changes in growth rate must reflect an important demographic trend occurring in the rural areas of Owamboland. If the relatively high values found in Groups I and III are excluded, the net growth rate becomes 0.6%, a value far below the 1.8% rate estimated for rural areas in the country as a whole (Table 1). In fact, these rural areas include local towns to which people migrated. Therefore, it could be stated that the overall trend in the area is out-migration, and that rural areas have a limited capacity for absorbing people, even when experiencing low population density.

III. Farming Conditions of Small-holders

The four villages selected for household surveys are shown in Fig. 2. Demographical statistics for these villages are listed in Table 2. The population density values are quite diverse, depending on the location of the villages. Village 1 belongs to the densely populated Group II in Fig.3, and Village 2 belongs to Group I, which lies near Oshakati township. Village 3 forms part of a discrete area of high population around Okahao. The least populated village 4, to which migration started in the late 1960s, was once a cattle post used for grazing in the dry season.

When comparing population density values among the villages, differences in

Table 2. Demography and areas of the four villages surveyed.

	Population (2001)	Number of household	Area Km^2	Area excluding oshana	Population density 1	Population density 2*
Village 1	493	64	6.44	5.27	76.55	93.52
Village 2	586	97	14.61	7.83	40.11	74.85
Village 3	1,266	215	20.18	19.50	62.73	64.92
Village 4	585	103	32.46	32.46	18.02	18.02

* population density calculated on oshana free basis

the physiological conditions of villages should be taken into account. The proportion of oshana in the village should be excluded from the total area studied, as population density is closely related with the density of field cropping areas. Areas dominated by oshana were traced and calculated in a TM image, and the population density of each village was re-calculated on an oshana-free basis. These values are listed in Table 2 as population density 2. Based on this calculation, the population densities of Villages I and II increased dramatically. To examine the effect of population density on farming conditions, the relationship between household size (number of persons) and the area of pearl millet fields was analyzed (Fig. 5). This figure clearly shows that there is a positive correlation between household size and field area. This is not surprising, given that under subsistence agriculture, household members are inevitably engaged in feeding themselves through land cultivation. The regression coefficient shows that, on average, one person requires 0.5 ha per year for subsistence, which reflects the productivity of land under present agro-environmental and socio-economic conditions. Despite large differences in population densities among the villages studied, there was no clear trend in the relationship between household size and field area. If high population density directly causes fragmentation of the land, it follows that per capita field area would be reduced. Evidently, this is not the case.

Another aspect to be considered is the intensity of land use. As shown in Fig. 6, the typical land use units of a smallholding are: the homestead, crop field, kraal, and grazing land that has been fenced off from other areas to protect the cattle. At each of the four villages, these land use units were measured with GPS, and the resultant tracks were superimposed on a TM image. Fig. 7 illustrates the specific case of Village 3. In order to determine whether differences exist among the villages regarding the allocation of land use units within a smallholding, the population density in a given household

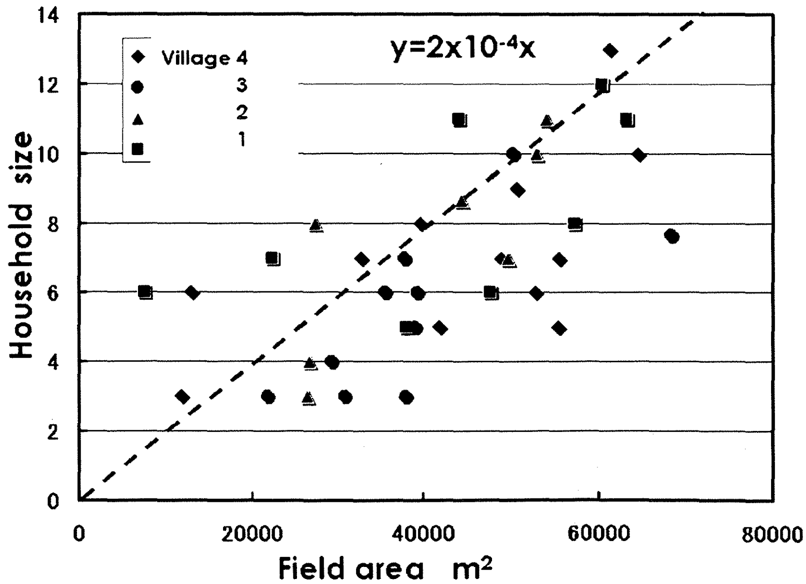

Fig. 5. Relationship between household size and the area of pearl millet field.

level was calculated in two ways. The first is based on the total area of a smallholding, and the other is based on the field cropping area (Fig. 8). The difference between the two values indicates the extent to which the crop field occupies the total area, or the intensity of land use for crop production. Regression lines for each village showed that Villages 3 and 4 had higher coefficient values than the other villages, demonstrating that the areas of smallholdings in Villages 3 and 4 were 2.2 and 2.4 times as big as the crop fields, respectively. The same analysis of Villages 1 and 2 yielded a similar regression line, showing that the crop fields occupied 68%, or 1/1.47, of the smallholdings. Fig. 8 clearly demonstrates that the number of people who depend on the field units

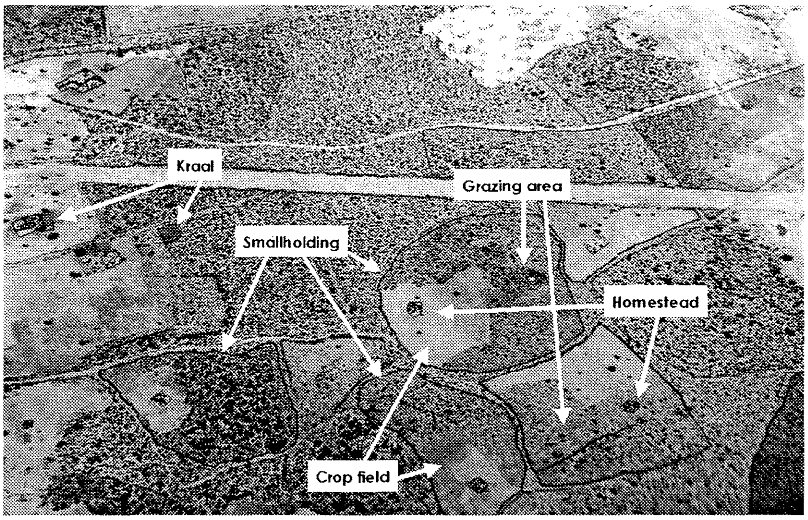

Fig. 6. Composition of smallholdings in the Ovamboland.

Fig. 7. Area calculation of smallholdings in Village 3.

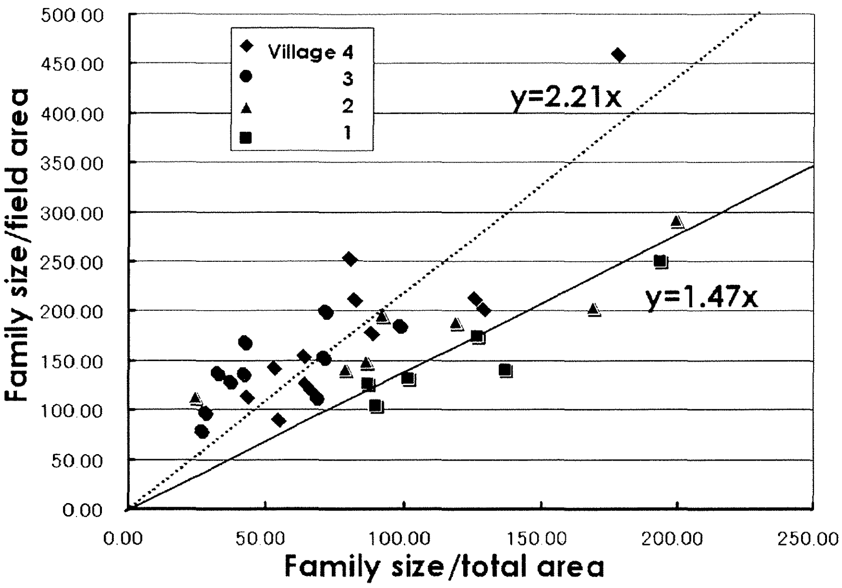

Fig. 8. Relationship between population density in relation to crop field size and in relation to smallholding size.

or smallholdings varies widely, although a mean value of 200 people/km^2/field was obtained in this study (Fig. 5). This variance may not ensue directly from the difference in soil productivity but may, instead, be the result of the farmers' socio-economic adjustments.

IV. Population Pressure and Land Use Intensity

As discussed in the previous section, land use intensity (the field:smallholding ratio) was higher in Villages 1 and 2 than in Villages 3 and 4. Population density might be one of the factors that differentiated them. Fig. 9 shows the relationship between the field:smallholding ratio and population density. The population density of each village was adjusted on an oshana-free basis (population density 2 in Table 2). A positive relationship between these factors is evident, although this is based on a limited sample size. There exists a demonstrable land shortage in Villages 1 and 2 (Groups II and I, respectively, Fig. 3), where high population density has forced much of the population to enlarge their pearl millet fields while diminishing the size of grazing land within their smallholdings. The field:smallholding ratio of 68% may be the maximum value for crop production, considering the area of homestead, kraal, and fuel gathering required. The low population growth rate in Group II (Fig. 4) strongly supports the conclusion that the land shortage experienced within this area operates as a strong motivator for migration to urban areas.

CONCLUSION

An analysis of micro-scale changes in demography and land use intensity

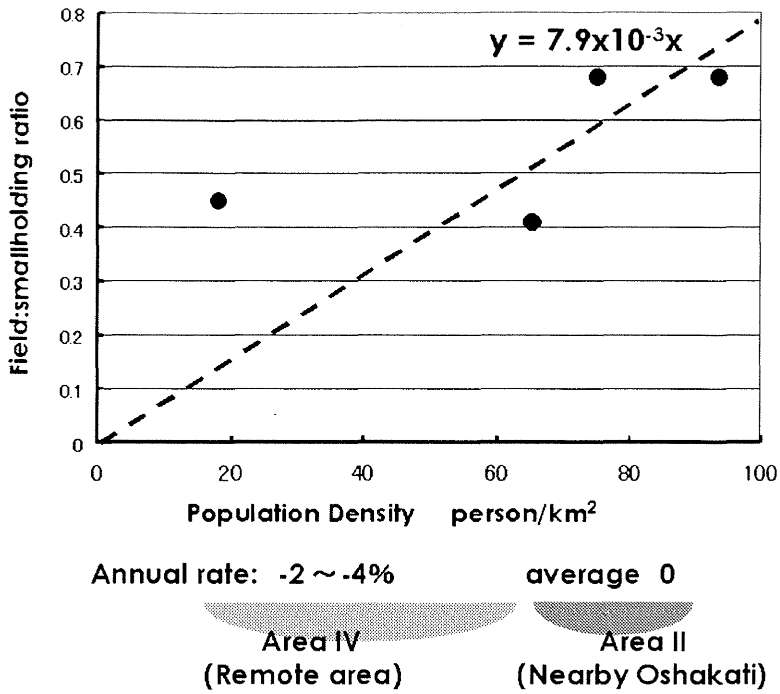

Fig. 9. Relationship between field:smallholding ratio and population density.

revealed that the population growth rate of rural areas remains extremely low, if migration to nearby local townships is excluded from consideration. Because the natural increase in population in rural areas is primarily absorbed outside the region, population pressure is not a real cause of environmental degradation currently found in the area such as continuous field cropping, overstocking of cattle and thinning of vegetation covers (Mendelsohn *et al.*, 2000). This conclusion may not be generalized over to the whole four northern regions, but at least in the studied area, it can be said that rural to urban migration can account for farmers' adaptive strategy to mitigate further stress to the area's fragile environment.

ACKNOWLEDGMENTS The author thanks Ms. L. Kafidi and Mr. A. Ryden of the National Planning Commission for their kind provision of the digitized census data for the studied area. This study was financially supported, in part, by a Grant-in-Aid for Scientific Research (Project No. 13371013 headed by Dr. Kazuharu Mizuno, Kyoto University) from the Ministry of Education, Science, Sports, Culture, and Technology of Japan.

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VEGETATION CHANGES AND USE OF PALMS AS A BUILDING MATERIAL BY OVAMBO AGRO-PASTORALISTS IN NORTH-CENTRAL NAMIBIA

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ABSTRACT This paper focuses on the mutual transition between vegetation and timber use by the Ovambo people in north-central Namibia and their use of palms for timber in recent years.
The vegetation around the research area was characterized as Mopane savanna, dominated by *Colophospermum mopane*. Historically, the Ovambo used mainly Mopane trunks for timber. However, as bush encroachment advanced in some parts of north-central Namibia, residents were forced to collect Mopane timber from the south. Since the 1970s, however, collecting Mopane has become difficult, and the inhabitants have therefore begun to use palm petioles for timber. Because the use of this resource requires many palm petioles, an environment conducive to grow many palms is required to make this option feasible. The vegetation configuration of this environment was formed mainly by three factors: (1) the unique flood terrain initially dispersed palm seeds over a wide area, (2) humans involuntarily dispersed seeds after eating, (3) palms were conserved by the residents. Thus, the increased use of palms emerged at a point of intersection between a change in vegetation patterns and a change in plant use by humans. The critical points of this use are its sustainability and the maintenance of traditional building complexity.

Key Words: Ovambo; Palm use; Mopane savanna; Vegetation change; Namibia.

INTRODUCTION

The vegetation environment in southern Africa has changed rapidly in recent decades, particularly in response to human impacts. In the Republic of Namibia, deforestation and bush encroachment are considered serious problems (Erkkilä & Siiskonen, 1992). In particular, the north-central region of the country has a high population density, and vegetation has been considerably disturbed in this area.

The local vegetation was once classified as Mopane savanna (Giess, 1971), which was dominated by *Colophospermum mopane*, a member of the family *Caesalpiniaceae*. However, Mendelsohn *et al.* (2000) discovered several patches of vegetation that were dominated by *Acacia arenalia*, which belongs to the family *Mimosaceae*. Previous work has demonstrated that this vegetation has formed as a result of bush encroachment (Mendelsohn *et al.*, 2000; Strohbach, 2000).

Ovambo agro-pastoralists primarily inhabit this region, and they use several tree species for various purposes, similar to other southern African societies.

Rodin (1985) conducted an ethno-botanical research study of the Ovambo and reported their tree utilization methods in detail. For example, the Ovambo use trees for food, medicine, timber, firewood, and instruments. Rodin (1985) pointed out that they used many trees for building materials, and this method of timber use has led to changes in the vegetation configuration of this region (Erkkilä & Siiskonen, 1992; Erkkilä, 2001).

On the other hand, changing of vegetation itself has influenced the tree utilization methods of the Ovambo. Particularly near towns, where deforestation and bush encroachment have increased rapidly, the local population has had difficulties collecting timber. At the same time, the socioeconomic conditions in this area have also been changing rapidly within the last few decades; for example, the country gained independence in 1990. The socioeconomic changes have therefore altered the vegetation both directly and indirectly.

In the area of near town, a new method of timber utilization using palm petioles has emerged in recent years. It is considered that palm use for timber is important as it enables sustainable timber use and maintains traditional method of house construction.

The use of palm petioles for timber has been reported by Marsh & Seely (1992) and Sullivan *et al.* (1995). They pointed out that Ovambo people use palm petioles for timber in these days.

However, it has not reported about historical change between their palm use for timber and vegetation change, especially bush encroachment. And it also has not discussed the meaning of palm use for timber in recent Ovambo society. So to examine the palm use for timber in the recent years, we need to clarify the historical change in timber use and compare the timber utilizations of people who live in different vegetation types. This paper focuses on the mutual transition between vegetation and timber utilization by the Ovambo and their use of palms as a building material in recent years. The research was conducted in two villages located in areas characterized by different vegetation types, Mopane savanna and patch vegetation that were dominated by *A. arenalia*, to compare the differences in timber utilization.

RESEARCH AREA

I. Study Site

The study was conducted in the villages of Onkani and Uukwangula. Onkani lies approximately 60 km southwest of the town of Oshakati, the center of the Oshana region in north-central Namibia (Fig. 1). Uukwangula is approximately 10 km west of Oshakati. The study was conducted over 7 months, from September 2002 to March 2003.

According to the official census, around the time of the study 590 people in 103 households lived in Onkani, and 590 people in 97 households lived in Uukwangula (Census Office, 2001). Although the populations of the two villages

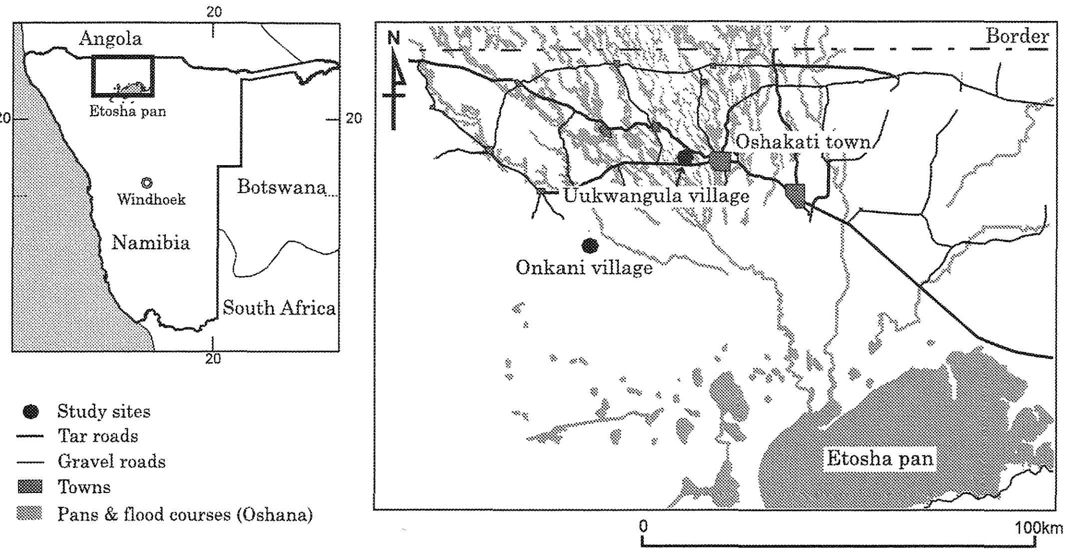

Fig. 1. Study site.

were the same, the population densities differed: 18.02 people/km^2 in Onkani and 40.11 people/km^2 in Uukwangula.

II. Climate and Environment

The research area is located on a vast plain at an elevation between 1090 m and 1110 m above sea level. The plain descends in a gradual slope from north to south, and many ephemeral flood courses extend from the Sierra Encoco Mountains in southern Angola to the Etosha pan in Northern Namibia; these flood courses are called "oshana" in the Ovambo language(1). In north-central Namibia, many oshana are densely distributed and collectively form a "flood area"(2).

The mean annual rainfall of this region is 400–500 mm, and the rainy season lasts from December to April. When the rains in southern Angola are heavy,

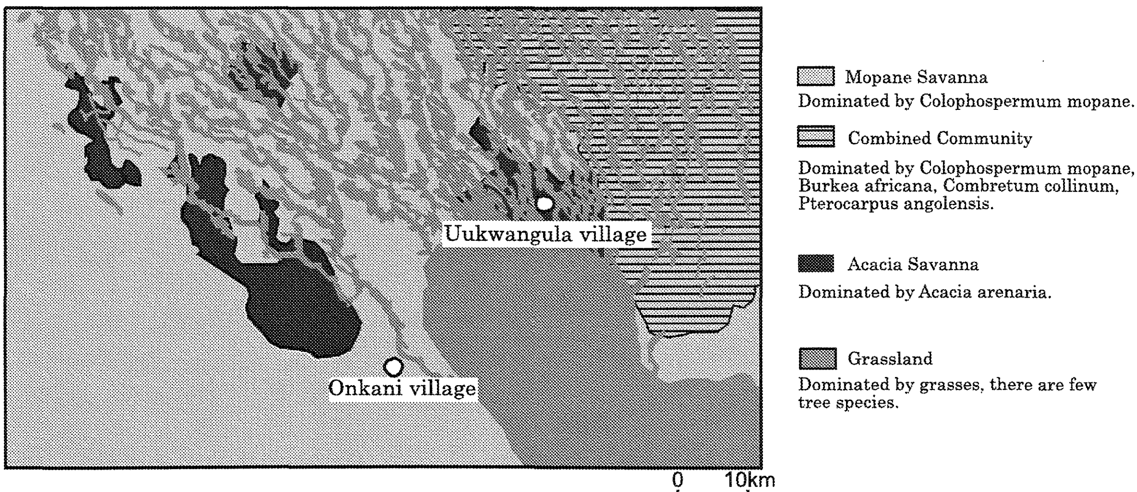

Fig. 2. Vegetation distribution in north-central Namibia. (Mendelsohn *et al.*, 2000).

floodwater moves to the south; this happens on average twice every 3 years (Clarke, 1999). Onkani is located outside the flood area, and there are no oshana near the village. On the other hand, Uukwangula is located in the center of the flood area and lies between two oshana.

The vegetation around Onkani is Mopane savanna, which is dominated by *C. mopane* (Mopane). Uukwangula lies in the Acacia savanna, which is dominated by *A. arenaria* (Acacia); this is an area where bush encroachment has advanced (Fig. 2). In the oshana, the primary vegetation is grasses, and few trees grow there.

III. History and Subsistence System

"Ovambo" is a generic name that describes several tribes, and nine Ovambo tribes are found in this country (Mendelsohn *et al.*, 2000). The two study villages are inhabited primarily by Kwambi people, who belong to one of these tribes. The Ovambo immigrated into north-central Namibia in the 16th century and separated into different groups on the basis of tribal affiliations (Williams, 1991). The Kwambi immigrated into the center of the flood area and inhabited the area near Uukwangula in the 19th century (Siiskonen, 1990). Therefore, Uukwangula is considered to have been founded at that time. In contrast, Onkani was established in the 1970s.

The Ovambo practice a multisubsistence system, i.e., agriculture, grazing, fishing, and gathering. They do not build houses in areas with oshana, nor do they cultivate fields there (Fig. 3). At the beginning of December, when the rainy season begins, the people cultivate fields that are located near their houses and sow pearl millet, sorghum, cowpea, and groundnut. Harvesting begins in May, at the end of the rainy season.

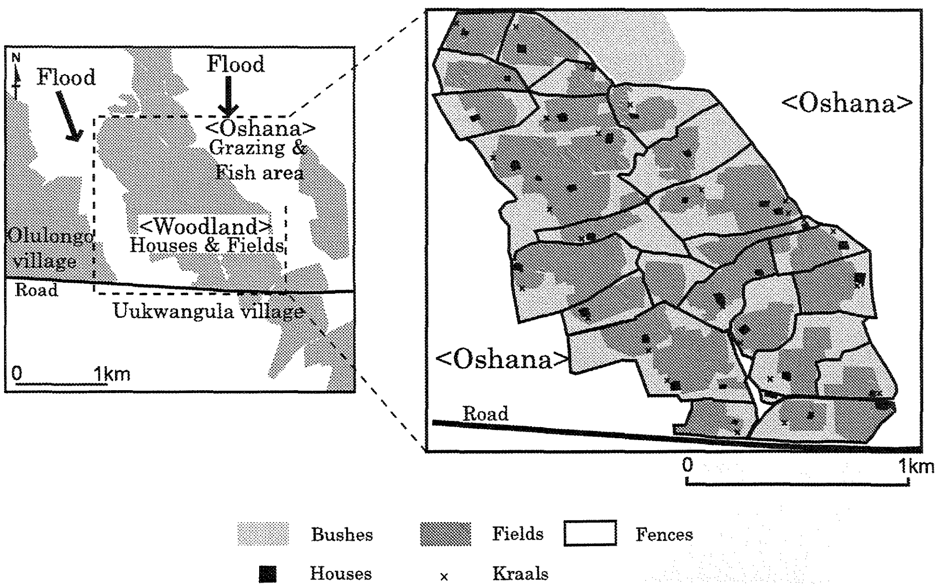

Fig. 3. Land use in the village of Uukwangula.
* This figure was drawn using GPS.

RESERCH METHODS

To evaluate the vegetation configuration, I established study sites on land owned by two households in each village. The study sites included fields and bush, and adjustments were made to allow for equal areas between the two villages (about 4.6 ha of bush and about 4.8 ha of fields per village). At these study sites, all trees >20 cm tall were counted and measured. The heights of palms were measured from the ground to the terminal shoot, excluding the leaves. In Uukwangula, all trees >4 m in height were counted and measured on the land belonging to 32 households to analyze the tree structure of the canopy layer (about 90.3 ha of fields and about 91.0 ha of bush). In the same area, all palms were counted and measured.

To evaluate timber use, I counted the number of 10-m-long logs used for the construction of outer palisades of 20 houses in Onkani and 32 houses in Uukwangula. I also interviewed the owners about their use of timber and how it had changed over time.

VEGETATION STRUCTURE IN ONKANI AND UUKWANGULA

I. Onkani

The history of Onkani is not as long as that of other Kwambi village, thus it is considered that the original vegetation is remained relatively. The vegetation around Onkani was classified as fields or bush. The vegetation on each parcel of land was surrounded by fences, but this village did not have a high population density; therefore, the communal area was not surrounded by fences and was located in the bush. In this village, Mopane trees accounted for more than

Table 1. Number of trees by height class in Onkani.

Tree species	Tree height (cm)							
	20–99	100–199	200–299	300–399	400–500	500<	Total	(%)
Bush								
Colophospermum mopane	1783	3400	586	8	1	1	5779	99.5
Hyphaene petersiana	0	0	0	0	0	0	0	0.0
Acacia arenaria	2	11	2	0	0	0	15	0.3
Others (3 species)	2	1	4	3	0	2	12	0.2
Total	1787	3412	592	11	1	3	5806	100.0
Field								
Colophospermum mopane	116	4	5	1	0	0	126	90.6
Hyphaene petersiana	7	1	1	0	1	0	10	7.2
Others (3 species)	0	1	1	1	0	0	3	2.2
Total	123	6	7	2	1	0	139	100.0

* Site area=ca. 4.6 ha of bush and ca. 4.8 ha of fields.

90% of all trees, both in the fields and the bush (Table 1). It was considerable that there were few other species in this village. *A. arenaria* that is the typical species in the bush encroachment area emerged only 15 trees in the bush. The palms (*Hyphaene petersiana*) were also few, only ten palms were observed in the fields. This palm is an indigenous species that is distributed throughout parts of Southern Africa (Palgrave, 1993).

Short Mopane trees <3 m tall accounted for more than 90% in both bush and fields (Table 1), even though Mopane usually grow to approximately 10 m in height. However, these trees had been cut at the main trunk and had attained a shrubby stature as a result of many shoot branches. Presumably, tall Mopane had been growing in this area when people first immigrated into the village.

II. Uukwangula

Around Uukwangula, vegetation was classified as either grasslands in areas with oshana or woodlands in other areas. Residents constructed houses and cultivated fields in the woodlands and erected fences around their land (Fig. 3). The vegetation on each parcel of land was surrounded by fences and was classified as either fields or bush. Bush was dominated by *A. arenaria* (61.5%) and *H. petersiana* (33.1%: Table 2). The palms were dominant in the fields (75.8%), followed by *Sclerocarya birrea* (20.9%; Table 2). This finding represents one of the main differences in terms of vegetation between the two villages. The total number of trees was lower in the fields than in the bush, but the number of tall trees was higher in the fields. We focused on the tree structure of the canopy layer and found that the palm and *S. birrea* accounted for 91.4% of all tall trees (Table 3), followed by *Berchemia discolor* (3.0%). These tall trees are

Table 2. Number of trees by height class in Uukwangula.

Tree species	Tree height (cm)							
	20–99	100–199	200–299	300–399	400–500	500<	Total	(%)
Bush								
Acacia arenaria	188	397	64	0	0	0	649	61.5
Dichrostachys cinerea	11	31	1	1	0	0	44	4.2
Hyphaene petersiana	339	4	3	1	2	1	350	33.1
Sclerocarya birrea	0	0	0	0	0	10	10	0.9
Others (2 species)	1	0	0	0	0	2	3	0.3
Total	539	432	68	2	2	13	1056	100.0
Field								
Acacia arenaria	2	1	0	0	0	0	3	1.6
Dichrostachys cinerea	0	0	0	0	0	0	0	0.0
Hyphaene petersiana	108	2	5	4	8	11	138	75.8
Sclerocarya birrea	11	7	2	1	4	13	38	20.9
Others (2 species)	0	0	0	0	0	3	3	1.6
Total	121	10	7	5	12	28	182	100.0

* Site area=ca. 4.6 ha of bush and ca. 4.8 ha of fields.

Table 3. Number of tall trees in Uukwangula.

Species	Field	Bush	Total	(%)
Acacia sp.	2	2	4	0.6
Berchemia discolor	16	3	19	3.0
Colophospermum mopane	1		1	0.2
Combretum sp.	8	1	9	1.4
Commiphora sp.		1	1	0.2
Diospyros mespiliformis	1	1	2	0.3
Ficus sycomorus	6	2	8	1.3
Hyphaene petersiana	228	191	419	66.7
Lonchocarpus nelsii	1	3	4	0.6
Prosopis glandulosa	1		1	0.2
Salix sp.	1		1	0.2
Sclerocarya birrea	115	40	155	24.7
Terminalia sericea	1		1	0.2
Others	2	1	3	0.5
Total	118	41	628	100.0

* Site area=ca. 90.3 ha of fields and ca. 91.0 ha of bush.
** Tall trees were defined as being >4 m in height.
*** Tree species with underline bear edible fruits.

edible fruit–bearing species, and the number of these species in the fields was larger than in the bush. Mopane trees were represented by only one individual in the fields (Table 3).

FACTORS AFFECTING PALM DISTRIBUTION

In an earlier chapter, the differences in the number of palms between Onkani and Uukwangula were illustrated. The reason for the differences is two-fold: ecological environments and human impacts. Figure 4 shows the locations of palm trees in a village within the flood area. According to this figure, the palms were distributed primarily near or in the oshana. One of the reasons for this is that this palm can grow in areas with sufficient water supply. As the groundwater aquifer lies at a shallow depth in the oshana (Marsh & Seely, 1992), sufficient groundwater is available. The other reason influencing the distribution of palm trees is the seed-dispersing capability of this species. This type of palm has male and female plants, and the latter bear many round seeds 4–6 cm in diameter. Seeds of this size are not readily dispersed by wind. Instead, animals, in particular baboons and elephants, disperse the seeds (Codd, 1972); however, these animals are rare in the flood area. However, because the seeds float on water, they are easily dispersed by flooding. Through this route of seed dispersal, palm seeds drift ashore and then germinate. This seed-dispersal system is an important factor for palm distribution within the vast flood area of north-central Namibia.

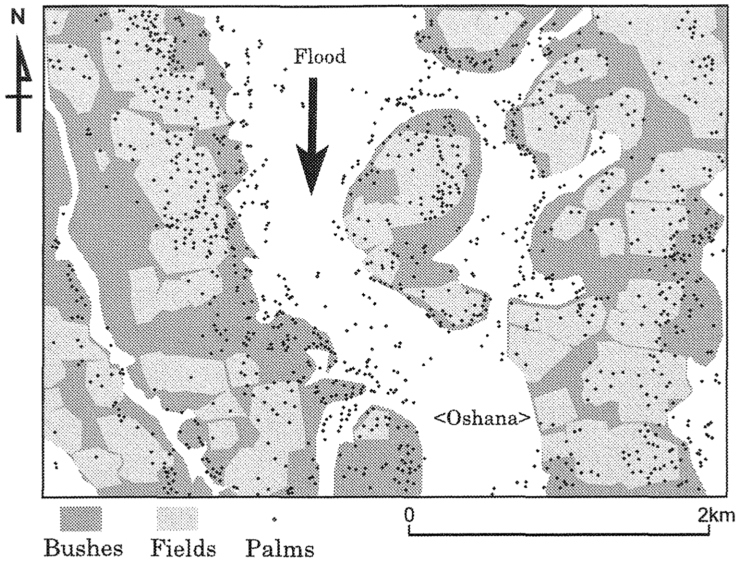

Fig. 4. Distribution of palms in one village in north-central Namibia.
* This figure was drawn using an aerial photo taken in 1996.

In addition to this factor, anthropogenic activities also influence seed dispersal. The Ovambo deliberately plant few seeds of indigenous trees. However, they often eat this palm fruit near the end of the dry season, and after they eat the fruit, they discard the seeds; this results in the involuntarily dispersal of many seeds throughout the village. Figure 4 also illustrates that there are many palms inside the fields, which are located near the houses, where many palm seeds are often dispersed.

In addition to seed dispersal, the conservation of fruiting trees has also been an important factor in increasing the number of palms (Cunningham, 1997). One reason for their conservation is that palm fruits are an important part of the food supply during the dry season. Another reason is that fruit trees were traditionally managed by a village headman (Kreike, 1995), and villagers were not allowed to fell fruit trees without the permission of the headman. In recent years, this system has changed, and the house owner now manages the fruit trees that grow on his own land, which is fenced in. Despite this change, the people still conserve edible fruit–bearing trees, and they manage seedlings of these species. In recent years, residents have used tractors to plough their fields. Despite this, small palms still grow in the fields because the villagers avoid cutting them down while ploughing. Approximately 30% of small palms (<1 m in height) grew in the fields (Fig. 5).

Another reason for not harvesting the palms is that the people earn money by selling palm products, such as palm liquor ("okanyome") and palm baskets ("oshimbali"). The Ovambo produce okanyome from palm fruits and weave oshimbali with palm leaves. They regularly drink okanyome and use oshimbali to store food and other items, and they have sold these palm-based products in the city. In particular, since the country gained independence, palm products have been sold to tourists as souvenirs and to Ovambo workers in the city.

The villagers of Onkani make okanyome and oshimbali, despite the scarcity

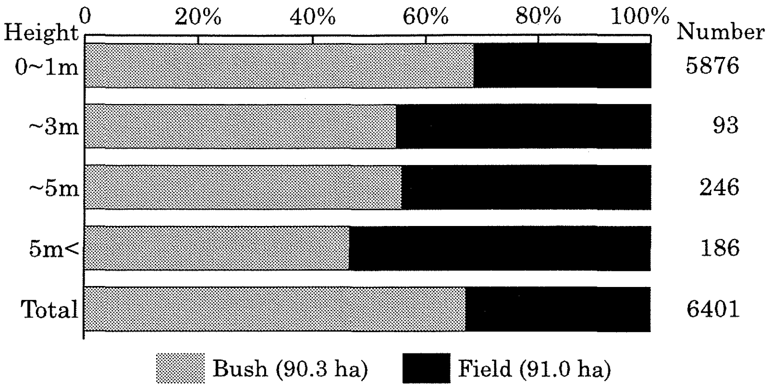

Fig. 5. Habitat of Palm tree.

of palms in their area. In fact, all households made oshimbali because it is essential for their daily lives, and it is easy to carry the material (palm leaf) from other places. Ten people (50%) sold oshimbali during the last year (2002). In contrast, only five households made okanyome, because of the difficulty of collecting enough palm fruits.

On the other hand, in Uukwangula, 21 households (66%) make and sell okanyome. The okanyome is often sold in small shops in the center of the village, where shop owners sell to traders from the city, and some people sell their products directly to traders. Thirty households (93%) make oshimbali, and 12 households sold them during the last year.

In summary, because the palms are important in the daily lives of villagers and can be used to generate revenue, they have been conserved for a long time. At the same time, palms have also become an important source of timber in recent years.

TIMBER USE IN ONKANI

I. Use of Timber in House Construction

The Ovambo use timber to build houses, kraals, and fences. The house is called "egumbo" and has a complex structure composed of outer palisades, several huts, and inner palisades (Fig. 6). This complexity is an important feature of the houses. The traditional outer palisade requires many logs, ranging from 2–3 m in length. When a new house is built, the size and location of the house are selected and a ditch is excavated around the area to create the outer palisade. Logs are then densely arranged in the ditch and several huts are constructed within the outer palisade. Finally, several sections are divided by constructing the inner palisade, which is made in the same way as the outer palisade. Usually, Mopane logs are used for timber, along with stems of *Combretum hereroens* and *Terminalia sericea* (Rodin, 1985), which are strong and resistant to termites. House construction requires many logs; for example, 1380 logs were used in building a house (Fig. 6).

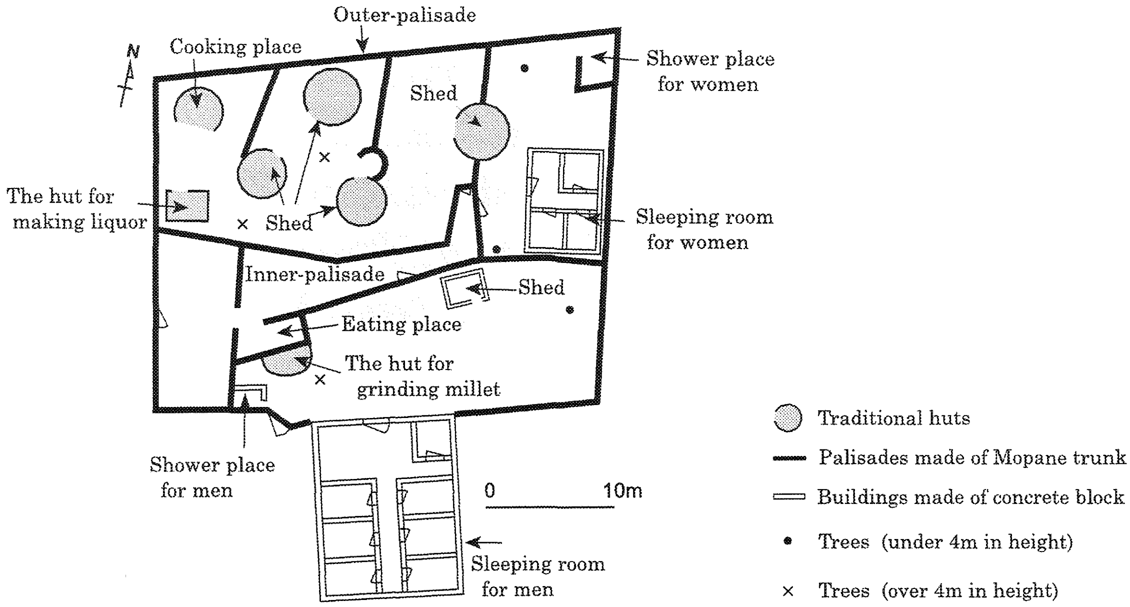

Fig. 6. Typical house structure.
* This figure was drawn based on one house measured in Uukwangula.

II. Use of Mopane for Timber

One of the earliest records of Ovambo life was written by the explorer Francis Galton, who reported on the structure of typical Ovambo houses when he visited this flood area in 1851 (Galton, 1889). Galton described the complex houses as labyrinths made of many logs.

In Onkani, people use mainly Mopane trunks as their building material. The outer palisade is classified into four types on the basis of the materials used: Mopane type, palm type, block type, and combined type (which consists of Mopane timbers and palm petioles). In this village, most of outer palisades are of the Mopane type (95%), and there are no palm-type or combined-type outer palisades (Table 4). Although many Mopane-type outer palisades are present, the ratio of thick Mopane stems (upper part at least 5 cm in diameter) that can be used is regulated by law, and many villagers used small Mopane branches (Table 5).

Palm petioles are seldom used in this village because the palms are sparsely distributed and few tall palms are available. On the other hand, many shrubby Mopane trees grow in dense stands, and people can use many small branches of these Mopanes. They also use the stems of pearl millet as a building material, especially for the inner palisades.

TRANSITION OF TIMBER USE IN UUKWANGULA

I. Use of Mopane for Timber

When the Kwambi people immigrated into Uukwangula, the vegetation in the

Table 4. Number of outer palisades by type in Uukwangula and Onkani.

Village name	Palm type number (%)	Combined type number (%)	Mopane type number (%)	Block type number (%)	Total number (%)
Uukwangula village	14 (44)	4 (12)	8 (25)	6 (19)	32 (100)
Onkani village	0 (0)	0 (0)	19 (95)	1 (5)	20 (100)

* The outer-palisade type was defined by the ratio of palm petioles used. Types that used palm petioles >80% were considered the palm type, types that used palm petioles <20% were considered the Mopane type, and types that used palm petioles between 20% and 80% were considered the combined type. Palisades constructed of concrete blocks were considered the block type.

Table 5. Average number of logs used for each outer-palisade type per 10 m length.

Type of Outer-palisade	Mopane trunks (cm)					Palm petioles (cm)		others
	0–5	5–10	10–15	15–20	20<	0–5	5<	
Uukwangula village								
Palm type (14)	6	9	4	1	0	178	131	2
Combined type (4)	26	23	10	3	0	24	40	0
Mopane type (8)	27	58	20	4	0	1	4	0
Onkani village								
Mopane type (19)	126	49	8	1	0	0	4	0

area was Mopane savanna, and the people used the Mopane around the village for timber. However, bush encroachment increased owing to harvesting of Mopane and overgrazing, and the Mopane savanna was replaced by Acacia savanna. When this vegetation transition exactly occurred is unknown. An elderly villager reported that there had been very few Mopane trees around the village during his childhood.

Consequently, finding Mopane for timber near the village has become challenging. The villagers do not use Acacia trees for timber because the stems are too short and are easily broken. Therefore, people collect Mopane from other areas. For example, almost all households (88%) in Uukwangula collected Mopane from the southern area, especially around Onkani (Fig. 7). In the past, villagers were not allowed to freely cut down Mopane trees in other areas, because the areas in which natural resources could be collected were predetermined among the Ovambo tribes. For the Kwambi, this designated area was to the south, in a region that corresponded with the cattle grazing area during the dry season. Thus, the people collected Mopane timber in the south, and chose a location where many Mopane trees grew.

II. The Decline of Mopane Timber Use

Since the 1970s, it has been difficult to collect Mopane timber in the south. One reason is that the number of Mopane trees with thick stems decreased as a result of overharvesting. Mopane trees produce many new branches, resulting in a shrubby stature, and many years are required for the trees to achieve sufficient height and diameter for use as timber. Currently, almost all the Mopane

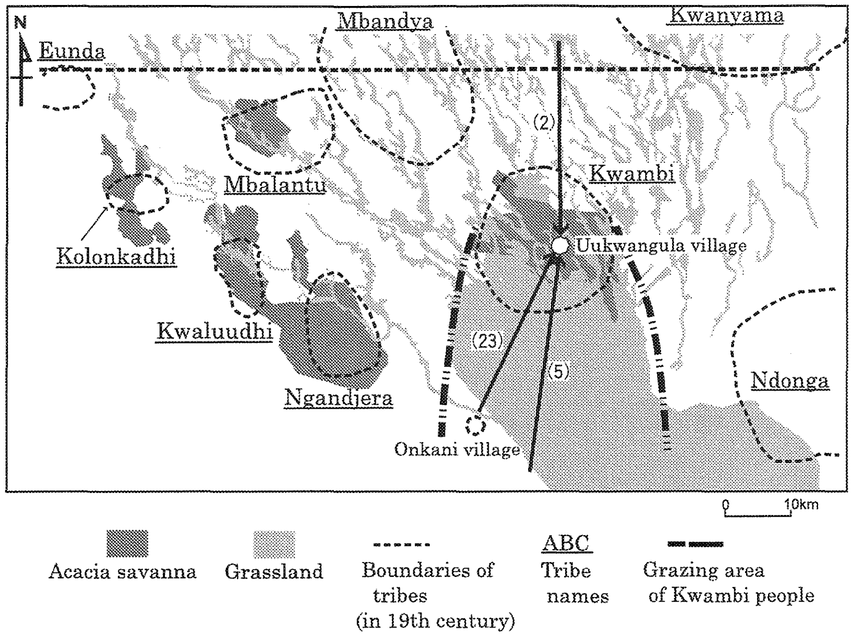

Fig. 7. Area in which Mopane timber is collected by Uukwangula villagers.
* The number of households is shown in parentheses.
** The tribe boundary is based on Siiskonen (1990); vegetation distribution is based on Mendelsohn *et al.* (2000).

trees around Onkani are <3 m in height[(3)] (Table 1). The Uukwangula villagers indicated that the number of tall Mopane trees has been in decline since about the 1970s.

Another reason for the decline is the population migration, which was prompted in part by a scarcity of land. Some Kwambi people migrated from the flood plain to the southern area, which historically had a low population density; Onkani was formed by those people. The Ovambo population was 300,000 in 1970, 450,000 in 1980, 630,000 in 1991 (Mendelsohn *et al.*, 2000; Census Office, 1991); thus, the population increased over 2.1-fold in 21 years, from 1970 to 1991.

In addition, the war for independence intensified at that time; thus, the people took refuge from the central area to rural areas or to other countries, and some Kwambi people migrated to the south. Because of this migration, the number of Mopane trees with thick stems was rapidly reduced, and it became difficult for other villagers to collect timber.

Still another difficulty in using Mopane timber was legal prohibition. In 1968, the Forest Act was established, which prohibited the harvest of tall trees without permission. However, this measure was not effective in preventing the people from felling tall trees, because it was a chaotic period owing to the ongoing war of independence. The Uukwangula villagers indicated that the regulations became stricter once the country gained independence.

III. Land Use Changes in Uukwangula

For the reasons discussed above, the villagers of Uukwangula began to collect timber around their own village. However, land use has also changed in Uukwangula since the 1980s. One of these changes was that the residents erected fences around their land to protect their fields from domestic animals. Fuller *et al.* (1996) pointed out that people erected fences around their lands after government farms were fenced. Presumably, the people were anxious about the amount of land, which was decreasing as the number of houses increased.

The practice of erecting fences influenced the patterns of tree use. Historically, a village headman managed the village lands and assigned land to a house owner until the death of that owner; villagers returned the land after the death of the house owner. As mentioned earlier, the headman also managed tall trees. However, the system gradually changed such that the house owner managed his own land, including all trees growing on it. Erecting fences accelerated this tendency.

IV. Use of Palm Petioles for Timber

Because of these changes, the villagers of Uukwangula have changed their construction methods. Specifically, they now use concrete blocks and tin sheets, i.e., they have devised a new type of building using these new materials. However, only a few people use these materials to construct the outer and inner palisades, whereas many people now use palm petioles as a building material.

The villagers usually use long, thick palm petioles, called "iipokolo", as a building material. These petioles are collected from tall palm trees (>2–3 m in height), called "omulunga." At the end of the dry season, a villager climbs the omulunga and cuts down several iipokolo and fruits. The palm fruit is used for making okanyome. In 1 year, one omulunga produces 12–20 leaves on average (Fanshawe, 1967). The iipokolo is used for making the outer palisade, inner palisade, rooves of the huts, and kraal. The stems of pearl millet are also used as a building material, particularly for the inner palisade and the interior of the outer palisade.

In Uukwangula, most of the outer palisades were of the palm type (44%), followed by the Mopane type (25%; Table 4). On average, the palm type required 309 palm petioles and 20 Mopane logs (10 m long) for the outer palisade (Table 5). The Mopane type required five palm petioles and 109 Mopane timbers (Table 5). Thus, the palm-type outer palisade substituted 89 Mopane timbers for 304 iipokolo per 10-m length of outer palisade. The average length of the outer palisade was 98.5 m; thus, 2994 iipokolo replaced 876 Mopane timbers. Although the Ovambo people have historically used iipokolo for various purposes, using this many iipokolo as a building material is a recent trend.

DISCUSSION

I. Factors Enabling the Use of Many Palm Petioles in Uukwangula

As indicated above, the timber use has changed because of vegetation and social conditions, and the villagers of Uukwangula used mostly palm petioles for timber. The main reason why they were able to build palm-type outer palisades was that palm petioles were readily available. Because palm petioles are thinner and weaker than Mopane timber, many petioles must be used together, and some petioles must be removed and repaired every year owing to decay and breakage. Moreover, palm petioles are used not only for the outer palisade but also for several other purposes. Therefore, many palm petioles are needed, and the use of palm trees depends on an environment that is conducive to the growth of numerous palms.

The main factors affecting palm distribution are geographical conditions and human impacts. This flood plain exhibits a particular geographical condition with a unique palm distribution pattern. In general, the palms grow along ephemeral or perennial rivers in arid regions. Namibian palms are distributed mainly along the Hoarusib and Kunene Rivers in northwestern Namibia and the Okavango and Kuwando Rivers in northeastern Namibia. However, palm growth is confined to riparian habitats, and the population of this species is not very large. Despite the low prevalence of this species, people use this palm for multiple purposes in these areas (Malan & Owen-Smith, 1974; Davelid & Hast, 1998), although they use fewer palm leaves than the villagers of Uukwangula. On the other hand, this flood area is subjected to many ephemeral flood courses, and the palms are therefore distributed over a vast area.

Anthropogenic impacts on vegetation were evaluated by comparing the vegetation of Uukwangula to that of Onkani. Human activities have led to a reduction in the number of Mopane trees and to bush encroachment as well as to an increase in the number of some edible fruit bearing species, especially palms. This change has caused an increase in the availability of palm petioles. The critical point of these ecohistorical changes is the mutual relationship between vegetation distribution and plant use by the people. Of course, other factors are associated with this transition, but the increase in palm populations is the most important factor that facilitates the use of many palm petioles. However, human activities are also important for increasing the number of palms. Thus, the palm-type outer palisade emerged because of the confluence of vegetation change and changes in plant use by the people.

In addition, this mutual transition has continued into modern times. In recent years, the villagers of Onkani have actively planted palm seeds, and the number of small palms in the fields has gradually increased. This trend is important for collecting building materials in the future, when the number of Mopane trees will be further reduced.

II. Palm Petioles and Recent Trends in the Use of New Materials

In recent years, most people have begun to use concrete blocks and tin sheets purchased in the city. Because Uukwangula is located near a larger town, bringing such items to the village is easy. All houses in Uukwangula have some components made of concrete blocks, and the outer palisades of six houses were constructed with concrete blocks (Table 4). These outer palisades were built within the last few years, and one house under construction also had an outer palisade made of concrete blocks.

However, people who lived in these block-type houses also cut down palm petioles during the dry season and used them to repair the inner palisades, fences, kraals, and huts. Petioles were collected not only from female palms but also from male palms. Therefore, people who live in houses made of new materials also require palm petioles; thus, palm petioles rank among the most important building materials currently in use.

III. Sustainability of Palm Use

The cycle of palm petiole use is renewable because the petioles reproduce every year. This renewable nature is an important concept for the use of natural resources, but this concept has some inherent problems.

One problem is that there are currently few medium-sized palms, i.e., 1–3 m in height (Fig. 5). The number of small palms, 0–1 m, was 13.6 times greater than trees >3 m (Fig. 5), and these small palms are considered to have increased in number. However, intermediate-sized palms represented only 1.5% of the population. Sullivan *et al.* (1995) analyzed these findings and pointed out the relationship between this palm population structure and the use of palm leaves by people and domestic animals. People sometimes eat the terminal shoots of the palm, especially in years of drought.

Another problem was caused by the division of land according to the increase in the number of houses. People used palms of their land, which were fenced in. However, the land area of each household was different. The palm density also differed according to the ecological conditions where people lived. The owners of houses with few tall palms faced difficulty in collecting enough petioles to maintain a palm-type outer palisade.

This paper aimed to clarify the transition of vegetation and the timber use by the Ovambo and focused on palm use in recent years. Through comparison of two villages in different vegetations, it was clarified that palm petioles have been an important material for the Ovambo who live in the area where bush encroachment has advanced in recent years, during which the vegetation and social environment have changed rapidly. It is especially important for them to preserve the "complexity" of their traditional houses (i.e., outer and inner palisades and many huts). To clarify the relationship between the Ovambo and plants in recent years, the changing vegetation and human lifestyle should be evaluated based not only on the natural environment or social conditions but also on their subsistence, economic activities, and political condition. Methods of palm population management and the effect on palm populations should also be evaluated in detail.

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NOTES

(1) The Ovambo language is called Oshivambo, but it includes several dialects. In this paper, I refer to Oshikwambi, one of the Oshivambo dialects.

(2) In this area, the flood waters move along the ephemeral river course (oshana), and it seldom occurs that water overflows from this ephemeral river. This condition is different from other floodplains.

(3) Werger & Coetzee (1978) reported that Mopane trees distributed in the southern part of this flood area are shrubby. However, elderly Onkani villagers claimed that tall Mopane trees had grown around Onkani in the past.

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FARMER'S SELECTION OF LOCAL AND IMPROVED PEARL MILLET VARIETIES IN OVAMBOLAND, NORTHERN NAMIBIA

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ABSTRACT A new and improved cultivar of pearl millet (*Pennisetum glaucum*), Okashana-1, was released in Namibia in 1990 and was rapidly adopted in Ovamboland. However, as most farmers do not buy new seeds each year, any genetic trials of the cultivar on actual farms would be affected by cross-pollination. The present study clarified the characteristics of Okashana-1, as found on actual farms. In addition, this research also examined the interrelationships between the environmental status, traditions, livelihood, and subsistence activities in the study area and the cultivar characteristics.

Key Words: Okashana-1; Pearl millet; Namibia; Ovamboland.

INTRODUCTION

In semi-arid areas, crop plant breeding programs and various other trials are undertaken to develop cultivars that can withstand the harsh environmental conditions and produce a reliable harvest. Most trials, however, ignore the important differences between actual farms and pilot farms, e.g., plants are watered regularly on pilot farms, while on actual farms watering is weather-dependent. There are also many differences among farmers; wealthier farmers can afford chemical fertilizer, but others cannot. Research-led plant breeding at agricultural research stations often ignored such real conditions of farmers, and participatory breeding is strongly recommended (Monyo *et al.*, 2000). The present study focuses on a pearl millet program in Namibia as one of the successful example of crop breeding and extension.

A program introducing new varieties of pearl millet in Namibia started late 1980s, with the assistance of the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) at Hydrabad, India (Rohrbach *et al.* 1999). Local farmers were involved from the early stage of the program in selecting favorable varieties brought from India.

Early maturity and bold-seeded varieties were preferred, and they were mixed as a composite that was later called Okashana-1. It was introduced in the 1990–1991 crop season in Namibia, and was rapidly adopted by farmers to the extent that it covered estimated 49% of the country's pearl millet field (Rohrbach *et al.* 1999).

It is important to note, however, that most farmers did not buy new seeds each year (personal observation). Rather, seeds were collected from former harvests because of the shortage of money or farmer's traditional way of thinking that they won't spend money for subsistence farming. Unlike a crosspollinated F1 hybrid, Okashana-1 is an open-pollinated variety whose germplasm is maintained as composite. As pearl millet is primarily open-pollinated, the genetic characteristics of the crop may change in each generation, if cross-pollination with local varieties is not carefully avoided. As a matter of fact, many farmers were not strictly cultivating genuine Okashana-1, but validating their own varieties through selecting desired characteristics for the next generation. This paper tried to find out the fate of an introduced Okashana-1 in farmer's field, and the multi-purpose use of pearl millet in the livelihood of the Owambo people was discussed.

STUDY AREA

The research was conducted from December 2002 to May 2003 in Onkani, a village located in Northern Central Namibia, commonly referred to as Ovamboland (Fig. 1). The village, situated approximately 80 km southwest of Oshakati, included 58 families and had a population of approximately 670 in December 2002. Most of the population belonged to the Kwambi ethnic group. Until the first settlement was built in 1968, the area had been used as cattle pastureland and was generally known as a cattle post (Shilunga, 1997). The mopane bush (*Colophospermum mopane*) grows throughout the village and is primarily limited to 1.0–1.5 m in height because of felling. The ground surface is sandy and therefore considered barren and unsuitable for crop cultivation. Annual precipitation from 1997 to 2003 ranged from 200 mm to 400 mm. The dry season lasts from May to October, and the rainy season extends from November to April. The dominant livelihood in the village is agriculture and most families have fields and cultivate pearl millet, locally known as *mahangu*. In addition, most families also have livestock, such as cattle and goats. Pearl millet porridge (*oshifima*) is a staple food and pearl millet beer (*ontaku*) is a common drink. The villagers' incomes consist of pensions or remittances from family members who work in town.

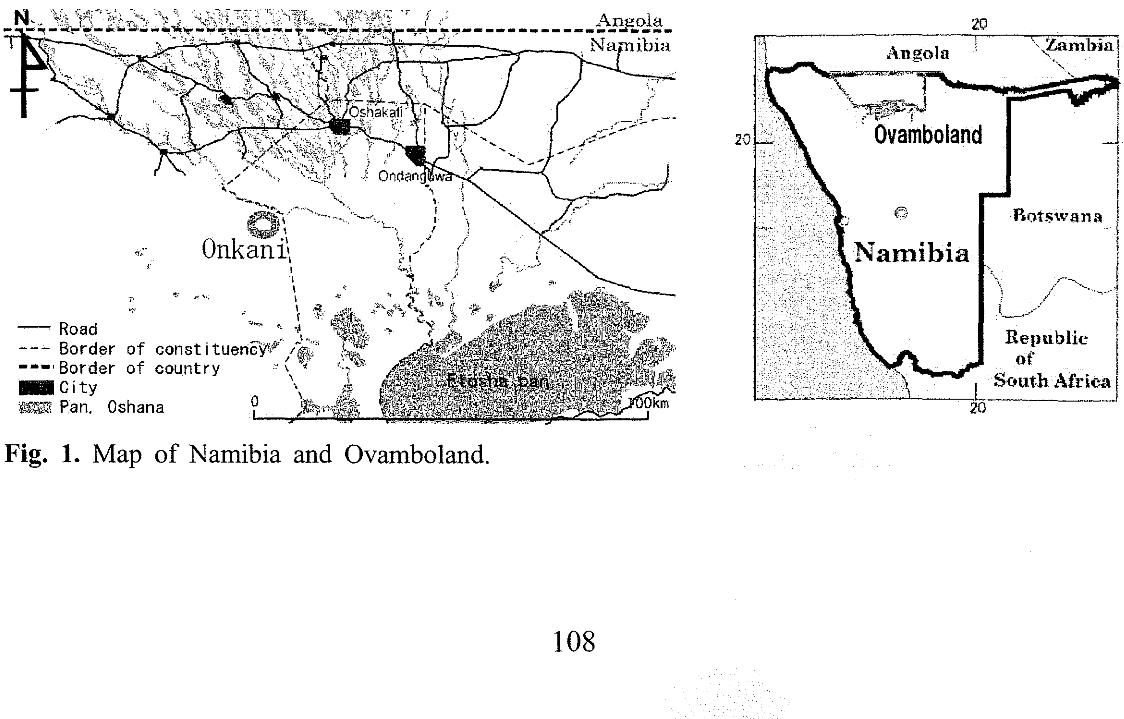

Fig. 1. Map of Namibia and Ovamboland.

FARMING

Most of the villagers have large fields, occupying over 4 ha on average, and over 90% of these fields are planted with pearl millet. Pearl millet is preferred over other cereals, because it is relatively drought resistant, tolerant of high temperatures, and can grow in sandy soils. There are many undulated hills of sand in the area and the upper parts of the hill slopes are used as pearl millet fields (Fig. 2), because the cereal is sensitive to flooding and the lower parts of the hill slopes are often flooded by heavy rains. All of the crops cultivated in the village are indicated in Table 1.

Plowing is generally started at the end of November, and sowing begins after the first heavy rainfall, and continues for several months. Weeding, the most labor-intensive aspect of the process, begins 2–3 weeks after sowing. Harvesting takes place between April and June. Threshing of the dried ears follows about one month after harvesting and the farmers store the harvests in large, traditional, granary baskets.

THE USE OF OKASHANA-1

Release of Okashana-1

Pearl millet is a food staple in Namibia, as it is the only cereal adapted to the low rainfall and high temperatures characteristic of most of the country.

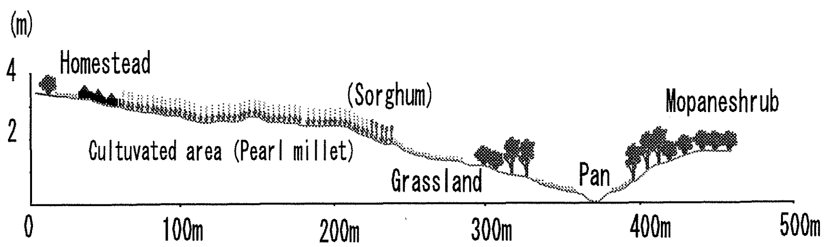

Fig. 2. Transect of cultivated area and pan in the study area.

Table 1. The variety of crops in the cultivated area.

English name	Scientific name	dialect name
pearl millet	*Pennisetum glaucum*	*mahangu*
sorghum	*Sorghum bicolor*	*oshijawara*
maize	*Zea mays*	*omapungu*
cowpea	*Vigna unguiculata*	*omakunde*
bambara nut	*Voandzeia subterranea*	*efukwa*
ground nut	*Arachis hypogaea*	*efungwa*
watermelon	*Citrullus lanatus*	*etanga*
calabash	*Lagenaria siceraria*	*omupanba*
pumpkin	*Cucurbita moschata*	*oshihenda*

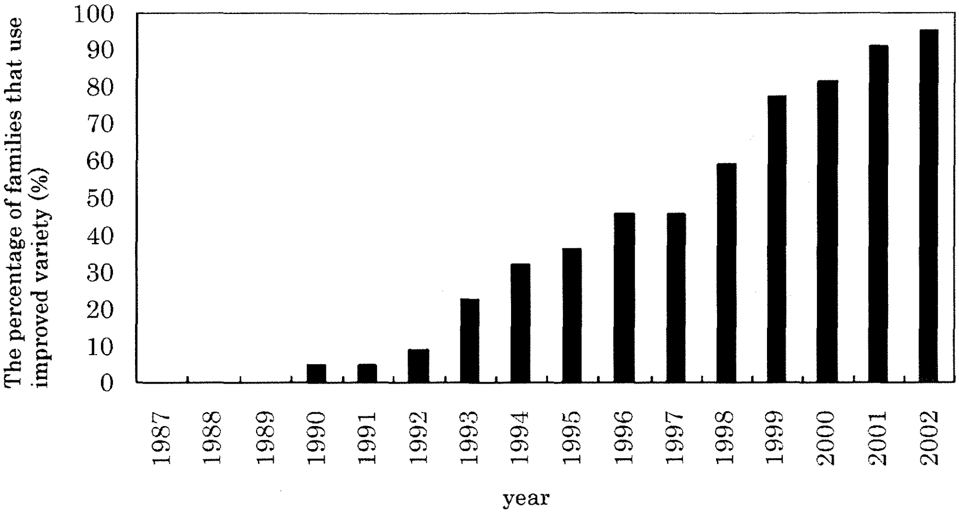

Fig. 3. The popularity of improved varieties of pearl millet in the study area (N=22).

However, because of shortages in the pearl millet harvest, the country depends heavily on cereal grain imports. Maize, wheat, and rice are commonly imported, particularly from South Africa. Improvements in pearl millet productivity are essential for both national and household food security. Namibia's pearl millet program provided farmers with the new cultivar, Okashana-1, developed by ICRISAT. Okashana-1 was released in 1990 and was notable for its early maturity and high grain yield (Monyo, 2002). Okashana-1 matures in 75–90 days, while the local varieties take an average of 120 days. According to Rohrbach *et al.* (1999), Okashana-1 provided Namibia with an estimated 21,000 tons of additional pearl millet grain during the average harvest. By the 1996–1997 cropping season, Okashana-1 was sown on an estimated 49% of the country's pearl millet area. Also, two additional pearl millet varieties, Kangara and Okashana-2, with characteristics similar to Okashana-1, were released in April 1998. These improved varieties were accepted by many farmers in Onkani. Fig. 3 indicates that the number of farmers who introduced new varieties increased steadily and that, eventually, all but one of the 22 families had introduced new varieties by 2002. Farmers bought new seeds every 3–4 years, and otherwise gathered seeds from former harvests. While, pearl millet is primarily open-pollinated, the farmers have tried to preserve desired types.

Characteristics of Improved and Local Varieties on Practicing Farms

As mentioned above, the "improved varieties" may change on practicing farms, and these varieties should be distinguished from the "original improved varieties". In this section, the characteristics of the improved and local varieties on practicing farms are described. The effects of improved varieties on the interrelationship between the farmers and crops are also examined.

Twenty-seven plots (5 × 5 m each) were established at numerous pearl millet farms of varying fertility and with varying densities of other plants. Plant height, number of ears, above-ground biomass and the yield after threshing were measured. The harvest biomass was dried for about half a month after harvest and then weighed to calculate the efficiency of seed production. Fig. 4 shows the difference in the efficiency of seed production between local and improved varieties. It is clear from the figure that improved varieties, as a whole, are more efficient than local varieties in producing seeds whether they were fertilized or not. Considering the gradual change of seed production efficiency from improved to local varieties, the cross-pollination between the two varieties might have taken place in some extent. But it can be concluded that beneficial characteristics of improved varieties are preserved in farmers field. Perhaps this is because the practice of sowing was done by separating these two varieties. The local varieties were characterized by their above average height and biomass (Table 2). On the other hand, the improved varieties were characteristically shorter, produced less biomass, and had higher seed production efficiencies than local varieties. The short characteristic coincided with early maturation. No significant differences were found in the number of ears or the amount of yield. These findings differ from those of ICRISAT, who defined the original improved variety as an early maturing crop with high grain yields. In practice, while the characteristic of early maturity was seen in the improved varieties, superiority of yield was not. Presumably, these practical characteristics are related to the wide spread of Okashana-1.

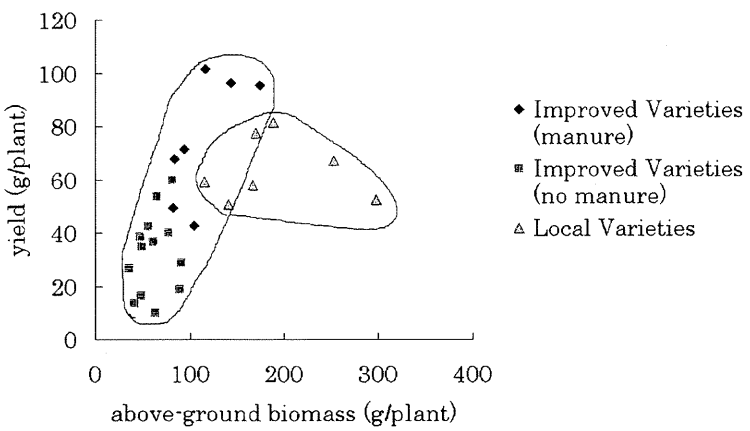

Fig. 4. The relationship between above-ground biomass and yield.

Table 2. Characteristics of local varieties and improved varieties from actual farms. The data presented are mean values (local variety, 7 plots; improved varieties, 20 plots).

	Plant height (cm)	Biomass (g/m^2)	Efficiency of seed production (yields/biomass)	Number of ear	Yields (g/m^2)
Local varieties	174	177	0.24	3.57	61.7
Improved varieties	151	90	0.33	3.67	51.8
	**	**	*	ns	ns

*, **, Significant at 5% and 1% levels of probability respectively.

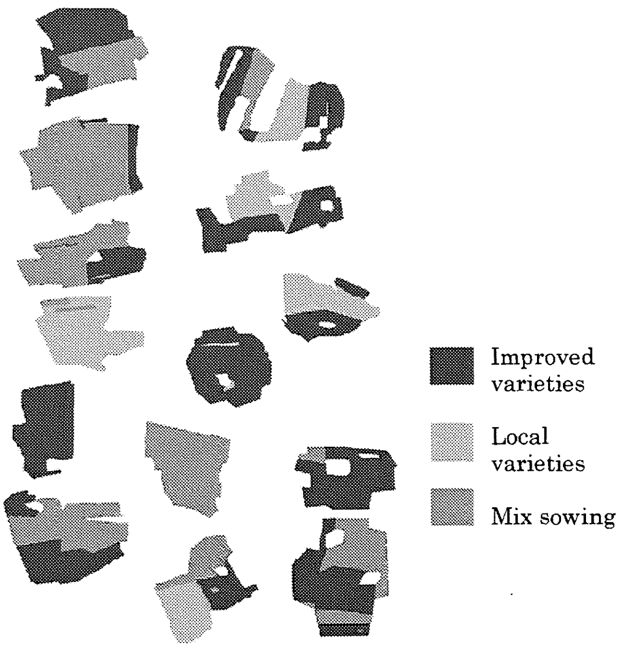

Fig. 5. The distribution of improved varieties, local varieties, and mixes on 14 farms.

Distribution of Improved Seeds in the Study Area

Twelve out of fourteen families were observed to use both the improved and the local pearl millet varieties. Furthermore, many families tended to sow these two varieties separately to prevent the cross-pollination (Fig. 5). But another opinion says that they are just doing their own "experiment" to find the difference between the two varieties. Their ordinal way of thinking is to sow them mixed which is also found extensively in the Fig. 5 either to breed a new variety or simply ignore the cross-pollination. Some farmers say that they don't mind cross-pollination because if the seed qualities became worse, they can buy new seeds then.

Reasons for Using Two Varieties Together

When asked their reasons for using both varieties of millet, farmers generally explained: "... we can harvest the improved variety if a particular year does not have enough rain. On the other hand, we can get more yield by the local variety when it rains enough ...", "... the improved variety is good because it matures early ...", and "... the local variety is good as building material ..." As stated above, most farmers saw the merits of both varieties.

Relationship between Rainfall Patterns and Adaptation of Varieties

When asked which year produced the best harvest, many of the 21 families queried answered 2000 or 2001 (Fig. 6). The 1999–2000 and 2000–2001 rainy seasons had had the highest rainfall for six years (Fig. 7). The 2000–2001 rainy season was about two months shorter than that of 1999–2000 (Fig. 8). The local varieties required approximately four months from sowing to harvest, while the improved varieties needed only three months. Considering these differences, and that it takes at least one month to sow an entire field, the 2000–2001 rainy season was too short for growing the local varieties.

To support the above result, I researched the percentage of the whole pearl millet area sown with the local varieties (Fig. 9). The families who had considered 1999–2000 as the best harvest year had largely planted local varieties. On the other hand, the families who had identified 2000–2001 as the best harvest had largely planted improved varieties. This observation further suggests that the rainfall pattern of the 2001 harvest year

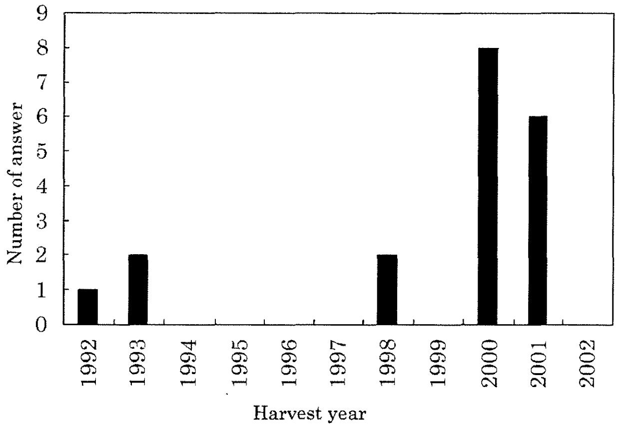

Fig. 6. The best harvest years.

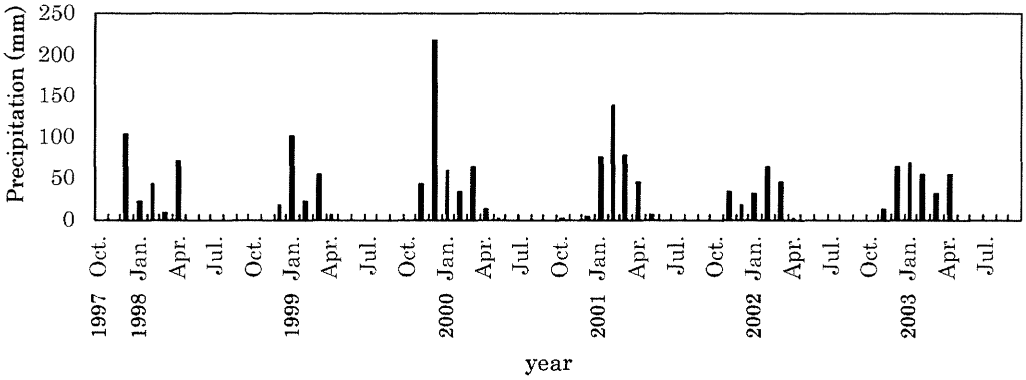

Fig. 7. Precipitation in Onkani village (1997–2003).

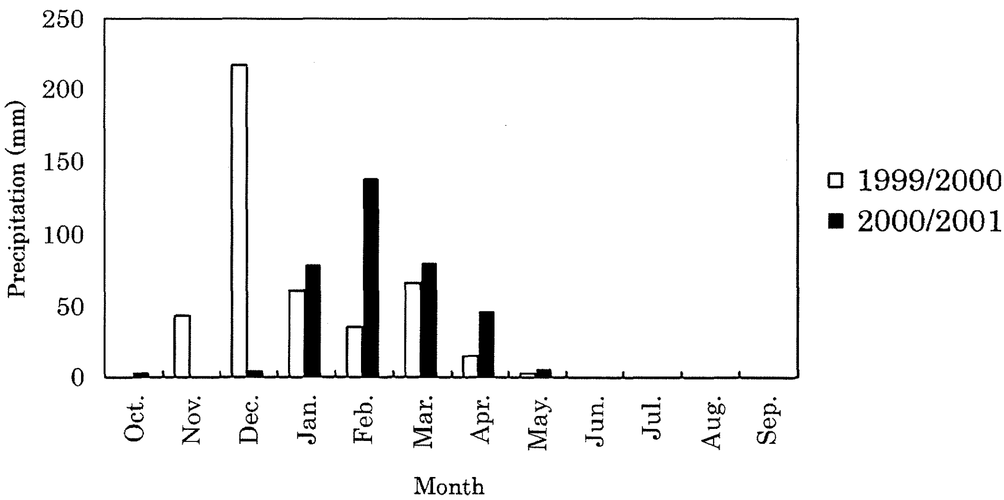

Fig. 8. Precipitation in Onkani village (1999–2000 and 2000–2001).

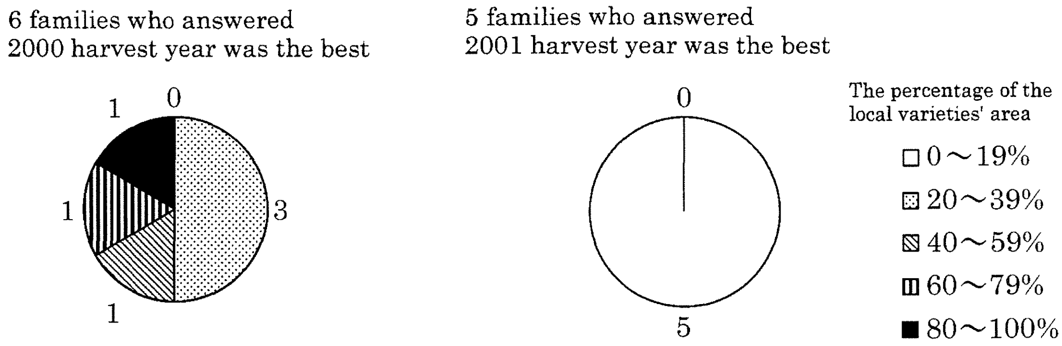

Fig. 9. The percentage of area cultivated with the local varieties, in whole fields of pearl millet, for six families who considered 2000 as the best harvest year (left) and for five families who considered 2001 as the best harvest year (right). The numerals indicate the number of families.

was more suitable for growing the improved varieties, and that the rainfall pattern of the 2000 harvest year was more suitable for the local varieties. As Fig. 7 shows, the pattern of rainfall changes very much from year to year, making it difficult for farmers to predict which variety will produce the greater yield. Therefore, many farmers find it important to use two varieties.

The difference between these two varieties with respect to the time of sowing should not be overlooked. Farmers in the study area tended to start sowing the improved varieties after they had finished sowing the local varieties. If farmers were to sow the improved variety, which matures early, at the beginning of the rainy season, they would be able to harvest by the end of the rainy season. In the study area, the ears of pearl millet are dried in the sun for about one month. Rain in this period would be problematic, as the moisture would trigger germination. Thus, farmers lacking roofed drying areas need to sow the improved varieties later, and effective use of the limited rainy season requires the sowing of both varieties.

The Value of Pearl Millet Stalks as Building Materials

The homesteads in the region include wonderfully designed wooden structures (Fig. 10). People use, primarily, mopane and the stalks of pearl millet for constructing the palisade fences that surround the homesteads and subdivide them into important areas, such as places to entertain visitors, sleep, cook, store grain, and a place to stamp grain. Approximately 4,000 poles would be used in a typical household (Marsh, 1994). The palisade fences must be taller than a person. The original function of the elaborate homestead fortification was to protect the inhabitants from both enemies and dangerous wild animals (Erkkila, 2001). Older residents reported that there used to be many big trees in the area in the past, but that they had been cut down for the construction of homesteads. The mopane bush, useless for palisade construction, covers most of the study area now, and therefore the stalks of pearl millet have become important substitutes for wood. The stalks of pearl millet are easy to carry and are in adequate supply, but need to be long to be suitable for the palisades. The local

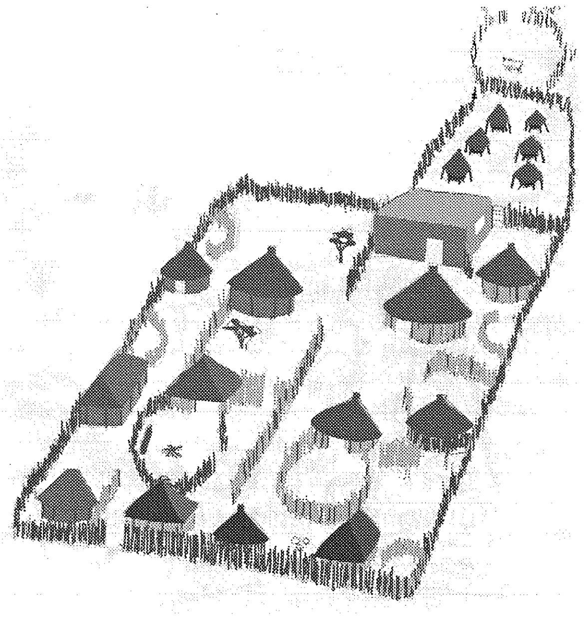

Fig. 10. A typical homestead structure in the study area.

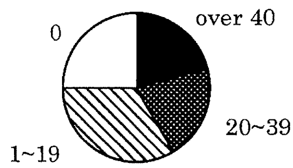

Fig. 11. The number of cattle owned by each family (N=24).

varieties are therefore preferred for building materials, as they grow tall. On the other hand, the stalks of the improved varieties are short and weak.

The Value of Pearl Millet Leaves and Stalks as Fodder

Livestock farming is also important in this area, and many families own cattle (Fig. 11). The seasonal cattle movement system is often practiced in Ovamboland (Mendelsohn & Roberts, 2000). There are four major movements each year in the study area. The first is in the rainy season, usually in February, when cattle are brought to densely populated areas where families live permanently. The cattle then feed on new pastures that have grown during the rainy season. In March, they are taken back to the cattle posts, located about 50 km from the village. The third movement occurs in June, after the pearl millet harvest. Cattle are then fed on the pearl millet stubble. Finally, they are taken back to the cattle posts. Goats are kept at home permanently. When cattle eat the stubble of pearl millet, they drop dung, an important fertilizer for the sandy, nutrient poor soil, especially given that most farmers cannot afford to buy chemical fertilizer. The larger biomass of the local pearl millet varieties was a significant source of fodder for the cattle. One family sowed about 2 ha with the local variety in the middle of February, too late to expect a successful harvest. It is conceivable that they sowed this vari-

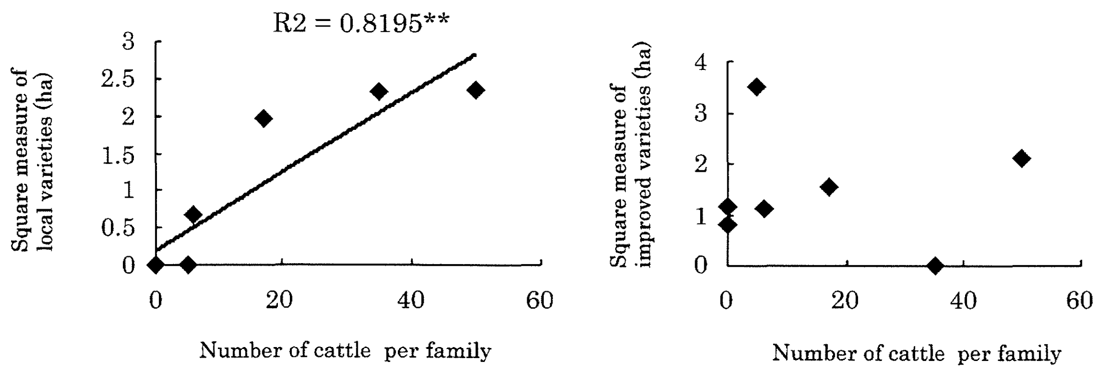

Fig. 12. The relationship between the number of cattle and the area cultivated with each variety.

ety at that time intentionally, not for grain production, but to provide fodder for their roughly 50 cattle. Fig. 12 displays the relationship between the number of cattle and the area of pearl millet fields for each of six families. No correlation was seen with the improved varieties, but the area cultivated with local varieties correlated closely with the number of cattle.

CONCLUSION

Comparison of growth characteristics of improved and traditional varieties of pearl millet in the farmers' fields revealed that despite continuous use of seeds from previous harvest, the characteristics attributed to improved varieties were preserved in the field, although cross-pollination with traditional varieties took place in some extent. This was ascribed to the fact that farmers grow the two varieties separately in the field. The improved varieties were short and were efficient seed producers. On the other hand, the local varieties were tall with greater biomass. Plant height was related to maturity period; improved varieties matured earlier than local varieties. Longer growing period of the local varieties increased the unreliability of the harvest because the pattern of rainfall was unpredictable, and the length of the rainy season was sometimes too short for the crop to mature. The improved varieties could compensate for the weak points of local varieties, and farmers accepted them easily and widely. On the other hand, the characteristics of the local varieties, i.e., the possibility of high yields, late maturity, long and strong stalks, and greater biomass, were also important to the traditional homestead and multi-subsistence strategies. In short, the rapid adoption of a new cultivar did not trigger the abandonment of the old cultivar in this study area. Farmers, taking into consideration the particular requirements of the climate and their lifestyle, largely selected to use both cultivars.

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HOLOCENE CLIMATE OF NAMIBIA: A REVIEW BASED ON GEOARCHIVES

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ABSTRACT The Holocene palaeoclimates in Namibia are reviewed by discussing different palaeoclimate geoarchives. The available evidence suggests little climatic fluctuations during the Holocene. There is evidence of more humidity compared to today during the early Holocene. Short dry episodes occurred around 8 ^{14}C-ka BP and around 5–3 ^{14}C-ka BP. Since 1000 years the northern Benguela Current sea surface temperatures show a decline and since ca. 500 years Namibia experienced in the Namib Desert and adjacent areas more arid conditions than before. Extreme flash floods occurred more frequently during the Little Ice Age, probably correlating to variations of sun spot activity.

Key Words: Holocene; geoarchives; palaeoclimate; Namibia.

INTRODUCTION

When the future greenhouse warming was first identified (see Oeschger, 2000), scientists informed about the potential impacts and implications of such change for selected aspects of the environment. It was tempting to turn to the past for analogues in the future. Yet, the isotopically inferred temperature record from Central Greenland and Antarctica (Fisher & Koerner, 2003) is not a template for all aspects of Holocene climate everywhere (Oldfield, 2003). If we accept that the climate past is the key for the climate future, we have to discuss the Holocene climate with its regional and short-term fluctuations for the geographic region under concern. So far there are some studies about climate change in southern Africa in the 20th century (Gerstengarbe & Werner, 2004; Mendelsohn *et al.* 2002; Heine, 1998a) and about scenarios for the future (Hulme, 1996; Hadley Centre, 2001) showing that climate change may not be uniform in southern Africa. Unfortunately, evidence of Holocene climate changes for Namibia is sparse, geographically scattered and often poorly dated. Here, I present a short review of the Holocene climatic history of Namibia based on a palaeoclimatic interpretation of geoarchives and archaeological findings.

RESEARCH AREA AND METHODS

Namibia is a large country, covering an area of about 823,680 km^2 and spanning some 1,320 km between ca. 17° and 29°S and roughly 12° and 25°E. Its coastline of approximately 1,570 km separates the land from the Atlantic Ocean. The general topographic pattern reflects three prominent elements: a narrow coastal plain (Namib Desert, 0–500/1000 m asl.), an eroded escarpment reaching altitudes of 1000/1500–2000 m asl., and an extensive interior plateau (Kalahari Basin, 1000–1500 m asl.). The Brandberg granite pluton rises to 2579 m asl. Most climatic features result from Namibia's position (Fig. 1). It is exposed to air movements driven by the Intertropical Convergence Zone, the Subtropical High Pressure Zone, and the Temperate Zone. The relative positions of the systems determine Namibia's rainfall. The cold Benguela Current is responsible for little rain, lower temperatures, stronger winds, frequent fogs, higher humidity,

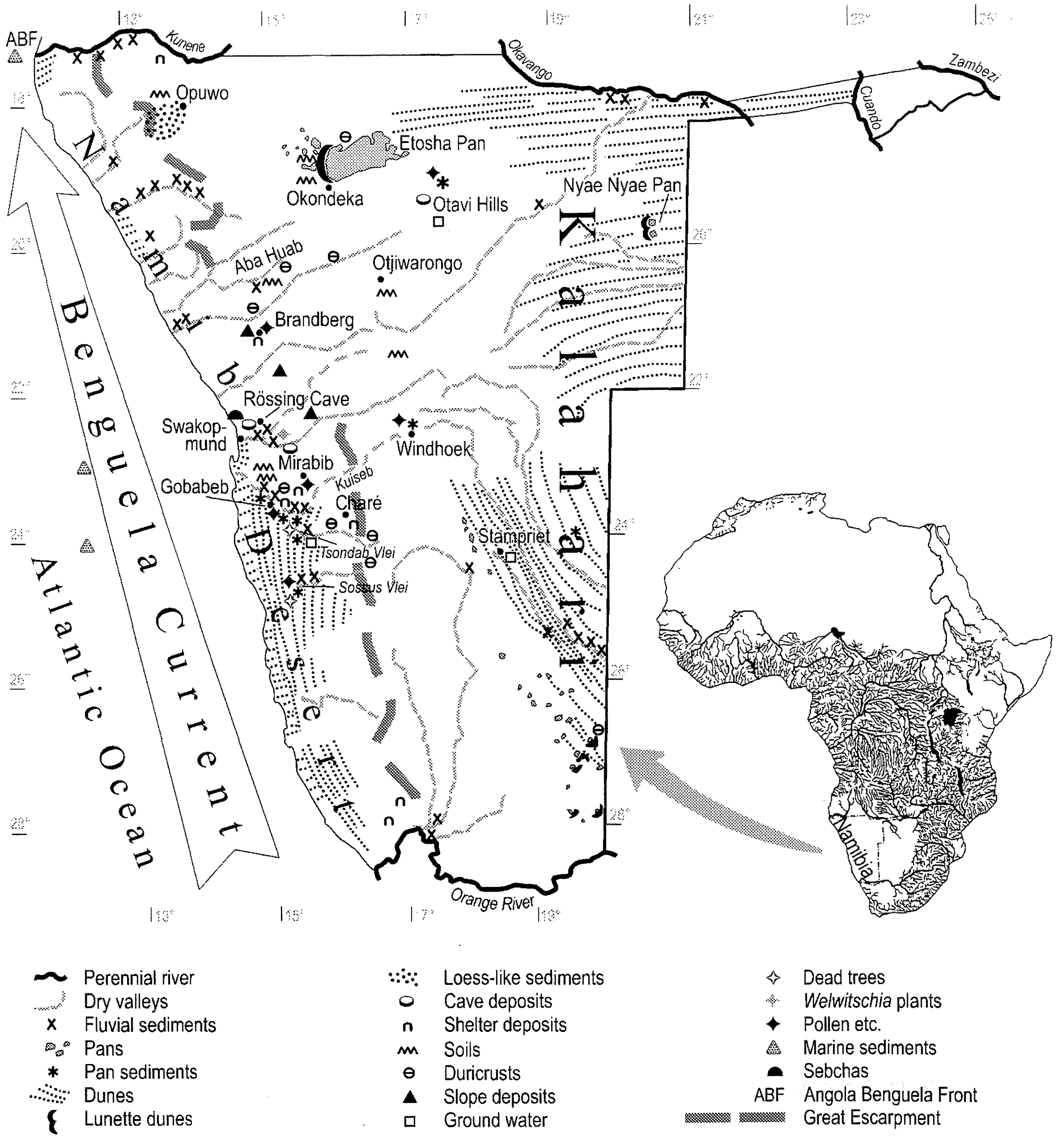

Fig. 1. Location map and localities of geoarchives in Namibia and pattern of perennial rivers in Africa (inset map)

less radiation and no frost along the Atlantic coast. Thermo-topographic airflows over the central Namib are found to have a regional significance frequently equalling or exceeding that of the general circulation (Lindesay & Tyson, 1990). The mean annual rainfall of less than 20 $mm.a^{-1}$ in the Namib Desert makes this region one of the driest in the world. To the northeast rainfall reaches >600 $mm.a^{-1}$. In the west (Namib Desert), dominant soils are arenosols, gypsisols, leptosols together with dune sands, gravel and rock outcrops. In the escarpment areas and mountains mainly leptosols and regosols are found, on calcareous rocks calcisols are common. In the Kalahari basin arenosols, and in the northwestern areas cambisols are widespread. Soils along the margins and valleys of larger river courses are fluvisols and in pans solonchaks and solonetzes are found (Mendelsohn *et al.*, 2002).

Holocene geoarchives that preserve one or more types of decipherable record of past environmental conditions and that can be used for palaeoclimatic reconstructions are the following: (a) dunes of the Namib Desert and the Kalahari region as well as the Etosha area, and desert loess, (b) fluvial deposits such as fluvial gravel, sand, silt and clay, slack water deposits, organic mud, from perennial rivers (Kunene, Okavango, Zambezi and Orange River) and from episodic and ephemeral rivers, (c) pan and lake sediments, (d) cave deposits (sinter, speleothems, sand), (e) soils, (f) slope deposits (debris), (g) groundwater, (h) trees (living and dead), (i) molluscs, ostracods, (j) pollen and hyrax dung, (k) marine sediments, and (l) sebhka deposits. In some cases a single archive will contain several possible proxies that can be translated into validated paleoenvironmental information (Oldfield, 2003).

Archaeological sites, documentary and instrumental records provide further palaeoclimatic information.

The current emphasis on climate reconstruction has led to an incredible diversity of proxy climate signatures (Oldfield, 2003). Most palaeoclimatic reconstructions from proxy records do not consider the fact that proxy records may represent either a general trend (within millennia: pedogenesis, vegetation changes etc.), a short phase (within several years, decades or centuries: lake-level fluctuations, lacustrine sedimentation, lunette dune formation etc.) or extreme climatic events (within days, weeks or months: flash-floods, debris flows etc.) The records from Namibia reflect the relative paucity of evidence in that part of the world (e.g. Street-Perrott & Perrott, 1993; Jones *et al.*, 2001; Heine, 2002), and in most cases these refer to precipitation. The need for chronological control on all records of Holocene climate change in Namibia has to be emphasized. Only by chronological control a high time resolution is achieved and permits close comparison between archives and sites. Hence, miscorrelations and misinterpretations are avoided.

A large variety of methods is applied by the different authors mentioned in this review. I refer to the original literature for detailed methodological information.

GEOARCHIVES

I. Dunes and Desert Loess

Extensive systems of stabilized, degraded or fossil aeolian landforms (dunes) are located in various areas of Namibia. In the Namib Desert complex linear dunes (Lancaster, 1989) and in the southwestern, northwestern and northern Kalahari simple linear dunes are the dominant form, whereas near pans and the coast other dune types, such as lunettes and barchans, are found. According to optical luminescence dates, middle and later Holocene linear dune reactivation occurred in the southwestern Kalahari from about 26 to 8 ka BP and around 4 ka BP (Thomas *et al.*, 1997, 1998; Eitel & Blümel, 1998; Stokes *et al.*, 1997a, 1997b; Heine, 2002). Lunette dune formation in the western Kalahari (Nyae Nyae pans, Heine, 1995) shows higher wind velocity ca. 8 ka BP and in the southwestern Kalahari aeolian activity occurred frequently throughout the past 18 ka, indicating that the factors controlling lunette sedimentation were markedly different from those determining linear dune mobilization (Lawson & Thomas, 2002). At the same time the final deposition of linear dune sand occurred in the southwestern Kalahari (Blümel *et al.*, 1998; Eitel, Blümel *et al.*, 2002; Thomas & Shaw, 2002). Investigations of the valley fills of the southwestern Kalahari (Heine, 1981, 1990) show dune building around 4.5–3.5 ^{14}C-ka BP and after AD 1850 due to invading cattle breeders. More arid conditions and/or higher wind velocity is documented in the Kuiseb valley near Gobabeb by encroaching dune sand into the valley about 300–400 years ago (Mizuno & Kotaro, 2003).

In northern Namibia (SW of Opuwo), loess-like sediments accumulated during the Middle/Younger Holocene (?) and during the last 3000 years (Brunotte & Sander, 2000).

New analyses of data sets of luminescence ages for the southwest Kalahari suggests that different aeolian forms (linear dunes, lunettes, sand sheets) have been active over different time scales in the past, have different sensitivities to environmental changes and have different time scales over which they record and preserve the palaeoenvironmental record (Bateman *et al.*, 2003). The same is the case in the Etosha Pan area (Heine, 1995). Palaeoenvironmental reconstruction must consider this.

II. Fluvial Deposits

Considerable effort has been invested into process-orientated studies of the nature and impact of flash floods. Palaeoflood and slackwater deposits (for description see Baker, 1987, 2003: 308; Saint-Laurent, 2004) that are to be found in many valleys have been used as archives for palaeohydrological and palaeoclimatic reconstructions (e.g. Baker, 2003; Heine, 2004a, 2004b; Eitel *et al.*, 2001, 2005). Earlier publications on fluvial forms and sediments in valleys — now interpreted as slackwater deposits and corresponding floodouts (Heine, 2004a, 2004b) — had been described as archives documenting more arid climatic conditions in the catchment than today (Vogel & Rust, 1987, 1990; Blümel *et al.*, 2000; Eitel *et al.*, 2001, 2005; Hüser *et al.*, 1998). There is evidence that during the early Holocene and since about 2000 years slackwater deposits were accumulated, with a period of more frequent flash-floods during the Little Ice Age (Heine, 1998c, 2004a).

In the southwest Kalahari, coarse fluvial gravels, erosion processes, stone pavements and dune sands blown into the valleys indicate a dry phase about 4 ^{14}C-ka BP (Heine, 1982).

The so-called Gobabeb Gravel, non-calcified gravels found at numerous localities in Namibia (Martin, 1950), are dated to the Pleistocene/Holocene transition period and are interpreted as sediments of larger rivers (Ward, 1987). For the Namib Desert, Lancaster (2002) reports a period of increased river discharge centred on 12–8 ^{14}C-ka BP.

III. Pan, Lake and Swamp Sediments

Anoxic lake and swamp deposits which preserve fossil pollen, are very scarce in Namibia. Palynological studies attempted on pan sediments from Sossus Vlei (van Zinderen Bakker & Müller, 1987) and speleothems from the Rössing Cave (pers. communication, L. Scott) provide no data on Holocene environmental changes. For the central highland, Scott *et al.* (1991) find wetter conditions ca. >7–6 ^{14}C-ka BP and drier climates after ca. 3.5 ^{14}C-ka BP. Gypsiferous (Mees, 1999) and calcareous deposits (Mees, 2002) of southwestern Kalahari pans are not dated with respect to climate change.

Calcareous lacustrine deposits are found in interdune areas of the Namib Sand Sea (Lancaster & Teller, 1988; Teller *et al.*, 1990). They do not provide any sound information about the Holocene climatic history because of poor dating (Heine, 1995).

IV. Cave Deposits (sinter, speleothems, sand) and Shelters

Investigation of Namib cave speleothems indicate that there was no sinter formation during the Holocene (Heine, 1998b; Heine & Geyh, 1984).

From stalagmite deposition in northern Namibia, Brook *et al.* (1999) conclude that the mid-Holocene was not substantially wetter than now, but that in the early and late Holocene significantly dry periods occurred according to lowering of the groundwater table.

From shelters in the Namib Desert Scott (1996), Sandelowski (1977) and Brain & Brain (1977) provided evidence for increasing aridity during the Holocene since about 5 ^{14}C-ka BP and since ca. 500 years, respectively. In the Kaokoland, archaeobotanical and archaeozoological data do not confirm any climatic variation (Albrecht *et al.*, 2001).

V. Soils and Duricrusts

Periods of pedogenesis indicate changing climate conditions (Heine, 1995). Marked climate changes did not occur during the last glacial cycle in the extremely arid central Namib (Heine & Walter, 1996; Lancaster, 2002). Several episodes of fluvial silt sedimentation and weak pedogenesis occurred in the basin of the Aba-Huab catchment (Eitel & Zöller, 1996) and appear to correlate with late glacial (LGM, Antarctic Cold Reversal) and Holocene (8.2 ka event) climatic phases (Heine, 2002). The archaeological site of Mirabib and Charé indicate more arid conditions during the last ca. 500 years in the eastern central Namib (Heine, 1995).

In the Etosha area, the formation of the Okondeka I-Soil (Buch *et al.*, 1992) comprises only the early half of the Holocene. TL-ages indicate dune sand movement since the Middle Holocene. In the Otjiwarongo area vertisol — kastanozem — calcisol soil associations, developed in fine-grained mid-Holocene sediments (Eitel, Eberle *et al.*, 2002), document weak environmental changes.

Duricrusts such as calcretes and silcretes have been investigated by many authors (e.g. Blümel, 1979, 1981; Eitel, 1994). Because the beginning, the duration and the termination of soil and duricrust development cannot be dated accurately, time-resolution is poor (Heine, 1995, 2002; Lancaster, 2002), correlation of phases of pedogenesis is impossible and palaeoclimatic conclusions are often contrary to the real climatic history.

VI. Slope Deposits (debris)

Holocene colluvia such as slope deposits and debris flow sediments, are widespread in Namibia. Apart from investigations together with prehistoric research (e.g. Richter, 1991), Namibian slope deposits of Holocene age are not analyzed and dated, although systematic investigations could yield detailed information about environmental changes during the Holocene (see Völkel 1995). The stratigraphies from different archaeological sites of the Namib Desert and adjacent areas show coarse and fine debris strata of early Holocene age at the base and silt/sand sediments (partly with organic material) in the upper parts of middle to late Holocene age (Richter, 1991).

VII. Groundwater and Spring Tufas

Noble gas, isotopic composition and chemistry of the Stampriet groundwater have provided data about late Quaternary climatic conditions, yet do not show significant Holocene temperature changes (Stute & Talma, 1998).

A lowering of the groundwater table in the Otavi hills in northern Namibia is documented by speleothem formation around 8 ka (Brook *et al.*, 1999).

Spring and waterfall tufas are common in the Namib Desert. These deposits have not been investigated as palaeoclimatic archives. Increased groundwater flow in the Namib Desert occurred ca. 12–8 ^{14}C-ka BP (Lancaster, 2002).

VIII. Trees and Plants (living and dead)

In some places of the Namib Sand Sea, dead *Acacia erioloba* trees, still standing and now devoid of groundwater, died out around AD 1400 in the Sossus Vlei area (Vogel, 1989, 2003). Dead trees of the Tsondab Vlei may have grown during a brief warm and wet 17^{th} century period, but died out around AD 1700 (Vogel, 2003). Moving dune sand covered trees in the Kuiseb valley 300–400 years ago (Mizuno & Kotaro, 2003).

The distribution of *Welwitschia mirabilis* shows that in the central Namib no young plants occur, whereas in the northern Namib old and young specimens are widely found. The *Welwitschia* plants of the central Namib could only have grown when soil moisture was sufficient over many years so that the plants were able to produce taproots from the surface to the deep lying groundwater table or moist strata. In the central Namib, on the gravel plains east of Swakopmund, the distribution of *Welwitschia* plants in terms of pattern and age suggests that the last period with favourable conditions for seed germination and the establishment of plant communities, occurred during the Little Ice Age.

IX. Molluscs, Ostracods, Diatoms

Mollusc, ostracod and diatom data and interpretation in terms of palaeoclimatic reconstruction with sufficiently high time resolution were not presented from Namibia. Many ^{14}C-ages of molluscs from many places all over the country have been published, but it is not clear whether the inferred timing of periods of climate change is certain, given their reliance on ^{14}C dates on carbonate material (Heine, 1995).

X. Pollen, Owl Pellets and Hyrax Dung

Local arid conditions prevent the formation and preservation of lake or swamp deposits with reducing conditions that could preserve fossil plant material like pollen (van Zinderen Bakker & Muller, 1987). Pollen from Holocene hyrax dung samples compare well with modern assemblages but marked variations of grass, succulent and woody elements, call for investigations of secondary variations in Holocene vegetation and climate (Scott *et al.*, 2004). The climate reconstructed by pollen from hyrax middens of the Kuiseb valley show warm and moderately dry conditions between ca. 970 and 930 years BP, and relatively cool, wet conditions between ca. 700 and 620 years BP (Scott, 1996). Micromammalian evidence for drier climate in the central Namib points to ca. 5200 ^{14}C years BP and the last 500 years (Brain & Brain, 1977; Avery, 1993).

XI. Marine Sediments

Off the Namibian coast at about 23°S and 12°E alkenone-derived past sea-surface temperatures show for the Holocene little time resolution and temperature variation (Kirst *et al.*, 1999; Rimbu *et al.*, 2004). An early Holocene arid period from 11 to 9.8 ka BP was associated with weakened upwelling and warmer sea surface temperatures (Shi *et al.*, 2000). Dupont *et al.* (2004) give alkenone-derived sea surface temperatures (SSTs) for the Benguela Current near the Kunene mouth that show a sharp decline in SSTs (>1°C) to modern values in the past 1000 years. Pollen (Shi *et al.*, 1998, 2000), organic components (Diester-Haass *et al.*, 1988), dust and clay minerals from marine deposits indicate that the Holocene conditions along the Namib Desert coast and the interior underwent but little changes.

XII. Sebhka Deposits

Sebhka deposits within the coastal plain of Namibia have not been used as palaeoclimatic archives. A complex interaction between fluvial, aeolian and pedogenic processes is postulated between the Namib playas and sebkhas by Eckardt *et al.* (2001).

PALAEOHYDROLOGY

Evidence from fluvial sediments, pollen, soils, pan deposits and dunes indicates several phases of increased humidity and surface runoff in Namibia. Namib pan deposits show that there were no marked hydrologic changes in the arid western areas during the late Pleistocene and Holocene (Teller *et al.*, 1990; Lancaster, 2002). In the Etosha area, also only but weak precipitation fluctuations are represented by late Quaternary dune and soil development (Buch *et al.*, 1992; Heine, 1992, 1995, 2002). On the other hand, in the southwestern Kalahari, aeolian processes, fluvial activity and pedogenesis document dry *and* wet phases about 19 to 13 ^{14}C-ka BP (Heine, 1981, 1982). This can be concluded from valley deposits that contain fluvial silt and clay deposits with a rich mollusc fauna intercalated with aeolian dune sand. Although of pre-Holocene age, the example from the southwestern Kalahari shows that only the synthesis of proxy records yield a reliable palaeoclimatic reconstruction (Heine, 1981). In the southwestern Kalahari fluvial sedimentation was caused by low to moderate river discharge during years with higher above normal precipitation (summer *and* winter rains, see also Lee-Thorp & Beaumont, 1995), whereas in the Namib valleys higher precipitation with low to moderate discharge may result in incision of valley floor deposits. Slackwater deposits and floodouts reflect extreme flash floods of only a very short duration (one to several days; see Jacobson *et al.*, 1995: 118–119). Yet, during an exceptionally humid rainy season, flash floods and slackwater/floodout deposition may occur repeatedly (e.g. during the 1933/34 rainy season in Namibia), when sediment-loaded floodwaters are diverted from the main flow to quieter areas where the load settles, forming several horizontal layers of silts and fine sands. Where sediment-loaded flash floods leave the narrow mountain valleys, the floods can spread and form floodouts where the sediment load settles as result of reduced carrying capacity (Scheidegger, 1991). Slackwater deposits and floodouts, therefore, do represent but extreme flood events regardless of the climate and the geographical region of Namibia. Slackwater deposits and floodouts do not document any changes of the general climate of a certain Holocene period *a priori.*

CLIMATE RECONSTRUCTION AND CONCLUSIONS

The major features affecting precipitation are the situation of the southern boundary of the Intertropical Convergence Zone and the upwelling system off the west coast of Namibia which has some unusual distinguishing patterns (Tyson *et al.*, 2003). It consists of a number of distinct upwelling cells. A sudden collapse of the Angola-Benguela front (ABF) allows a flow of warm water along the coast to cause the Benguela Niños and may cause precipitation in the northern Namib Desert (see Shannon *et al.*, 1986; Krapf *et al.*, 2003).

There is no record of Holocene temperature changes from Namibia. Alkenone-derived SSTs show a decline in temperatures ca. 1000 years ago near the Kunene mouth (Dupont *et al.*, 2004).

Although there have certainly been wetter and drier phases, Namibia's climate has been rather similar to what it is today for the Holocene (Fig. 2). Proxy records for early Holocene precipitation changes stem from cave speleothem, spring tufas and deposits of shelters documenting more humidity roughly between 12 and 8 ^{14}C-ka BP. On the other hand, dune mobilization occurred in the western and southwestern Kalahari. Grain size analyses of lunette dunes show higher wind velocities during a phase around 8 ka BP (Heine, 1995). Some fluctuations in humidity are dated between 5 and 3 ^{14}C-ka BP (only in southern Namibia?). For the last ca. 500 years, more aridity has been observed in the central Namib Desert and adjacent areas. Lunette dunes are less climatically discriminating than linear dunes in terms of the conditions which lead to their development (Lawson & Thomas, 2002).

Slackwater deposits and floodouts cannot be used as palaeoclimatic archives; yet, they document flash-flood conditions caused by extreme precipitation events in the early Holocene and during the last 1000 years, with a concentration of floods in northern Namibia during the Little Ice Age.

The terrestrial proxy climate signatures from the Namibian mainland do not present any information about temperature fluctuations during the Holocene. Only from marine archives a SST decline of >1°C off northwest Namibia is reported.

The proxy data of the palaeoenvironmental archives are extremely heterogeneous and show that the environments react with different sensibility to weak climatic fluctuations (see also Cohen & Tyson, 1995).

The period of the Little Ice Age seems to be an exceptional case. Only during the Little Ice Age apparently more frequent and heavier precipitation events occurred, which produced bigger flash-floods than today in the northern

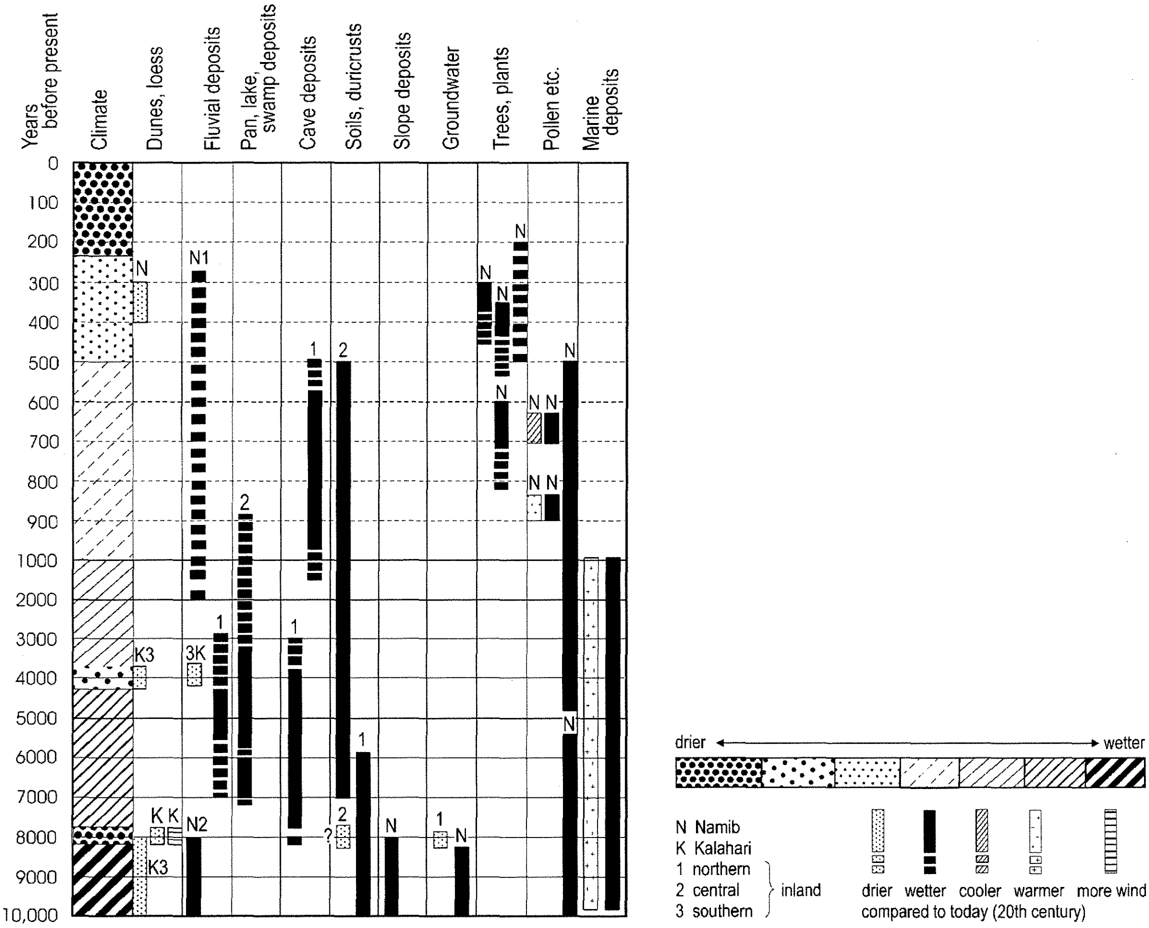

Fig. 2. Summary of dated evidence from different geoarchives for periods of increased and decreased moisture, phases with intensification of wind velocity, lowering of ground water table, soil formation phases etc. in Namibia

Namib valleys. It should be emphasised that climatic phases during which in Namibia slackwater deposits and floodouts were accumulated experienced a cooler and drier than normal climate in southern Africa (Heine, 2004a). These floods presumably were caused by small shifts of the Tropical Temperate Troughs (TTTs) over southern Africa and in the southwestern Indian Ocean corresponding to periods of reduced solar activity (Heine, 2004a). Recent studies of solar variability (Solanki *et al.*, 2004) and Holocene climate (Kromer et. al., 2004) call for a re-evaluation of the influence of solar activity variations on climate (Foukal *et al.*, 2004; von Storch *et al.*, 2004).

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FACTORS CONTROLLING GEOGRAPHICAL DISTRIBUTION IN SAVANNA VEGETATION IN NAMIBIA

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ABSTRACT Here, I describe the geographical distribution of the savanna types in Namibia and identify the factors controlling the occurrence of each savanna type in relation to the amount of annual precipitation and the various physiographical regions, including the mopane (*Colophospermum mopane*) area. The different types of savanna can be distinguished on the basis of the leaf habits of the dominant vegetation: deciduous, evergreen nanophyll, and evergreen notophyll. In general, vegetation performance (i.e., vegetation cover and maximum height) was positively correlated with the amount of annual precipitation. However, the occurrence of a particular savanna type coincided well with physiographical region regardless of the amount of annual precipitation received. Deciduous savanna occurred primarily in the Central Highland and had the smallest total vegetation cover among the three types. The dry soil of this region determined inevitably the deciduous leaf habit of the vegetation during the dry season and thus the smallest total vegetation cover. Evergreen nanophyll savanna was found mainly in the Mega Kalahari, where I observed a clear relationship between the amount of annual precipitation and total vegetation cover. The soil moisture in this region favored an evergreen leaf habit, even in the dry season, resulting in the effective use of soil water throughout the year. This probably accounted for the large increase in total vegetation cover with increasing annual precipitation. Evergreen notophyll savanna exclusively appeared in the mopane area, regardless of the physiographical region, and had the largest total vegetation cover, apparently as a result of the ecological characteristics of mopane. Therefore, it appears that the geographical distribution of the various savanna types in Namibia is principally controlled by two different factors that are independent of the amount of annual precipitation: the water-holding capacity of the soil and the ecological characteristics of mopane.

Key Words: Annual precipitation; *Colophospermum mopane*; Deciduous tree; Evergreen nanophyll; Evergreen notophyll; Savanna.

INTRODUCTION

Savanna vegetation occupies the broad region between dry deserts and humid forests in the tropics and subtropics (Huntley & Walker, 1992). Generally, it consists of a discontinuous crown cover of trees and shrubs with an undergrowth of grasses (Archibold, 1995). Savanna vegetation covers 40% of the land area of Africa (Okitsu, 2004a), and 65% of southern Africa (Scholes, 1997). In Namibia, it is the most representative type of vegetation (Okitsu, 2004b).

Savanna vegetation differs according to its environmentally broad distribution range, from desert to forest. These differences necessarily include not only changes in the performances of the vegetation, including tree cover and height, but also changes in the leaf habits of the vegetation, such as leaf size and seasonality. The leaf habits of savanna vegetation are major indicators of the environmental factors that influence the habitat, as discussed later in detail. Leaf habit closely corresponds to the water-holding capacity of the soil and/or the ecological nature of the dominant vegetation of a particular savanna. Thus, from a plant-geographical perspective, it is important to use leaf habit to identify physiographical factors controlling the type of savanna in a given area.

The geographical variations in vegetation from dry desert to savanna to humid forest basically correspond to the precipitation gradient (Knapp, 1973; Walter & Breckle, 1984; Archibold, 1995; Mendelsohn *et al.*, 2002). Earlier studies focused primarily on the relationships between the amount of precipitation and the performance of the vegetation (Knapp, 1973; Cowling *et al.*, 1994; Walter & Breckle, 1984). It was generally concluded that the observed differences in plant performance in the various vegetation structures of the tropics and subtropics could primarily be explained by the amount of precipitation.

I hypothesized that factors controlling geographical variations in savanna vegetation are not limited to precipitation alone, but are more complex and include leaf habits and plant ecological characteristics. However, only a few studies have focused on the different types of leaf habits in savanna vegetation. Huntley (1982) reported that the main functional distinction within southern African savannas could be described by leaf size, i.e., broad- and fine-leaved savannas. Scholes (1990) discussed the influence of soil fertility on the ecology of two types of southern African savannas, fine-leaved and broad-leaved, and schematically illustrated the association between environmental factors and leaf size (Scholes 1997). Despite these interesting studies, the factors controlling the geographical variations in the savanna types, as assessed by differences in leaf habits, remain uncertain. In this study, I identified the geographical distribution of different savanna types based on leaf habits and discuss the factors controlling their occurrence in relation to precipitation, physiographical regions, and areas of mopane (*Colophospermum mopane*) in Namibia.

STUDY AREA

This investigation was conducted throughout the territory of Namibia, located in southwestern Africa (17–27°S to13–20°E).

I. Physiographical Regions

Namibia can be divided into three major physiographical regions based principally on its landforms and soils: the Namib Desert, the Central Highland, and the Mega Kalahari (Fig. 1). The major landforms in Namibia are, from west to east, the coastal plain, the escarpment, the central plateau, and the Kalahari sand field (modified after Mthoko *et al.*, 1990). The pedology of Namibia is characterized by weakly developed (coastal plain), lithosolic (central plateau),

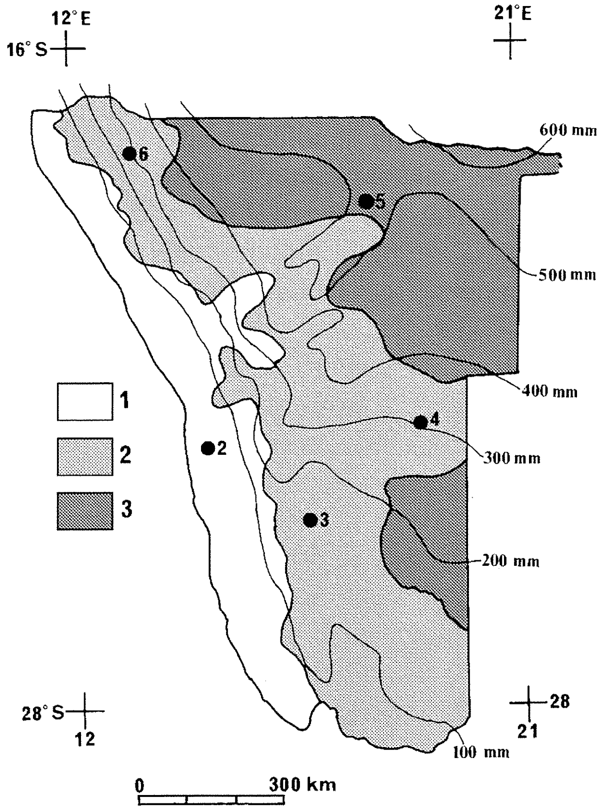

Fig. 1. The physiographicdal regions of Namibia (adapted from Erkkilae and Siiskonen, 1992, based on Mthoko *et al.*, 1990) and the distribution of annual precipitation (Koenen, 1996). The Capribi region (east of the Kavango River, slightly east-west between Zambia and Botswana) is omitted (also see Fig. 10). The dots with figure indicate the localities of the photos of Fig.2–Fig.6 (2: Fig. 2, 3: Fig.3, 4: Fig 4, 5: Fig. 5, 6: Fig. 6).
1: Namib Desert, 2: Central Highland, 3: Mega Kalahari

and arenosolic (Kalahari sand field) soil types (Erkkilae & Siiskonen, 1992; Mendelsohn *et al.*, 2002).

The Namib Desert occupies the coastal plain, which comprises the western marginal area between the escarpment and the coast, stretching along the entire Atlantic Ocean coastline and rising rapidly eastward. It extends 80–150 km inland and rises to a level of approximately 800 m at the foot of the escarpment in the east. The escarpment is situated at the east end of the coastal plains, rising steeply to the central plateau. The soils of this region are usually weakly developed, brown to grayish, and may or may not contain a B-horizon.

The Central Highland lies on the central plateau, east of the Namib Desert. The central plateau is a mountainous area situated between the escarpment in the west and the Kalahari sand field in the east, and rises 1,000–2,000 m. This area is characterized by highly undulating landforms, a thin soil layer, and an exposed bedrock stratum. The landforms typically consist of actively eroding landscapes, especially in the hilly or undulating areas that cover much of the central plateau. The ground surface tends to be hard, as it consists of rock or stones. The soils of this region are well represented by the leptosols, which are shallow, have a weak profile differentiation, and contain coarse rock debris, gravels, and solid bedrocks. These coarse-textured soils are characterized by their limited depth, due to the presence of continuous hard rock that consists of a highly calcareous or cemented layer within 30 cm of the surface. Accordingly, coupled with the highly undulating landforms, the water-holding capacity of the soils of this region is low, and vegetation on these soils is often subject to drought. The rates of water run-off and water erosion can be high during heavy rainfall.

The Mega Kalahari occupies the Kalahari sand plain, which is the area east of the Central Highland. The Kalahari sand plain consists of flat plains and smooth hills sloping gently to the northeast. The soils of this region are typically arenosols, which are formed from wind-blown sand and usually extend to a depth of at least 1 m, with sand generally making up more than 70%. The structure of these soils is usually loose, although calcrete layers occasionally occur near the surface. The loose structure of the arenosols, together with the flat plains and smooth hills of this region, allow for little run-off of water.

II. Climate

Namibia has a dry climate with extremely variable and unpredictable rainfall. In the study area, the average annual rainfall is less than 20 mm (15 mm in Swakopmund) on the coast and increases towards the northeast; Grootfontein receives 570 mm (Fig. 1). However, this distribution pattern of annual precipitation does not necessarily coincide with physiographical region (Fig. 1). The average annual potential evaporation varies between 3,700 mm in the central-southern area to 2,600 mm in the north (Erkkilae & Siiskonen, 1992; Mendelsohn *et al.*, 2002).

The range of temperature fluctuations throughout the year varies according to region. Generally, the hottest month is October, during which the average daily maximum temperature is 34–36°C. July is the coldest month in most parts of the country, except on the coast, where the lowest temperatures can be expected in August. The average daily minimum for the coldest month varies from less than 2°C to more than 10°C.

III. Vegetation

The vegetation of Namibia is divided into three major types (Giess, 1971; Koenen, 1996): the Namib Desert, savannas, and woodlands (after Erkkilae & Siiskonen, 1992).

The Namib Desert covers 15% of the territory of Namibia (Erkkilae & Siiskonen, 1992) and occupies the coastal plain. It consists primarily of scattered, non-woody vegetation, mainly herbaceous and succulent plants. Woody vegetation occurs in the Namib Desert only along the riverbeds. The plant diversity is very high, approximately 200-fold higher than in the Sahara Desert, which has a similar climate (Cowling *et al.*, 1998). However, what is called the Kalahari Desert in the eastern part of Namibia is not a genuine desert, but rather a type of savanna with scattered woods.

Savannas cover 65% of the territory of Namibia (Erkkilae & Siiskonen, 1992) and form a more or less discontinuous crown cover of trees. The savannas of Namibia consist of different types (Schultz, 1997). In the northeastern part of the country, savanna with a well-extended crown cover of trees predominates and consists mainly of scattered tall trees that are usually >15 m high. In the central part of the country, the dominant form is tree-shrub savanna, which is characterized by a scattered distribution of tall trees and low shrubs. In the southern and southeastern parts of the country, the Nama-karoo prevails. This type of savanna comprises deciduous low shrubs, scattered woods, and herbaceous plants. In addition, succulent-karoo occurs in the southeastern-most part of the country, consisting mainly of succulent plants mixed with low deciduous woods. In northwestern Namibia, the most common savanna type is dominated by mopane.

Woodlands have a continuous crown expansion that almost completely covers the land. They occur only in the most northeastern part of the country (Capribi), which receives the highest amount of rainfall (more than 600 mm), and account for 20% of the territory of Namibia (Erkkilae & Siiskonen, 1992). One of the dominant species in this region is Zambezi teak (*Baikiaea plurijuga*). The woodlands described by Erkkilae & Siiskonen (1992) correspond closely to the forest discussed in other major references (Archibold, 1997; Rutherford, 1997; Midgley *et al.*, 1997). Hereafter, the term forest or forests will be used instead of woodlands, consistent with the latter references.

METHODS

I. Leaf Habits and their Ecological Significance

Plants inevitably adopt the ecologically most adaptive leaf habits suitable to their environments. Thus, the leaf habit, which is aimed at maximizing photosynthesis, directly indicates the ecological adaptations of a plant (Chabot & Hicks, 1982). Here, I used two different features of the leaf habit, i.e., leaf size and seasonality, to analyze the different types of savanna in Namibia.

Leaf size corresponds well with the environment of a particular habitat, although it is a simple indicator. Table 1 presents a representative classification of leaf sizes. Under conditions of drought or low temperature that may occur during a growing season, leaf size tends to be small. For example, in subtropical warm temperate forests of Japan, a shift occurs from notophyllous to microphyllous evergreen broadleaves along the drought gradient between valleys (moist) and ridges (drought) or from the foothills (moist) to the mountains (drought) within fairly similar temperature regions (Ohsawa, 1993). A similar shift in leaf size in the transition from moist slopes to dry rocky slopes has also been observed in Mt. Pulog, Philippines (Buot & Okitsu, 1999). In the mountains of the tropics, where increasing altitudes are accompanied by

Table 1. Leaf size classes according to the Raunkiaer-Webb classification system (Shimwell, 1971).

Leaf size class	Size range (sq. mm) (Raunkiaer, 1934; Webb, 1959)
Leptophyll	< 25
Nanophyll	25–225
Microphyll	225–2,025
Notophyll	2,025–4,500
Mesophyll	4,500–18,225
Macrophyll	18,225–16,4025
Megaphyll	>16,4025

decreasing temperatures, leaf size usually decreases from mesophyllous in the lowlands to notophyllous in the lower montane, microphyllous in the upper montane and subalpine, and nanophyllous in the upper subalpine regions. These types of changes occur on Mt. Makilin (Brown, 1919) and Mt. Pulog (Buot & Okitsu, 1999) in the Philippines, in New Guinea (Grubb, 1974), and on Mt. Kerinci in Indonesia (Ohsawa & Ozaki, 1992). Thus, a decrease in leaf size generally follows a gradient ranging from more favorable to more stressful habitats (Buot & Okitsu, 1999).

In this study, only two major leaf sizes were observed in the dominant woody species of the study area: (1) nanophyll, in which the area of a leaf or leaflet ranges from 25 to 225 mm^2, e.g., the leaves of *Acacia* species, and (2) notophyll, in which the area of a leaf or a leaflet ranges from 2,025 to 4,500 mm^2. The most prevailing type of woodsy vegetation in the study area is mopane.

Seasonality is another ecologically important leaf habit that reflects adaptations to seasonal fluctuations, including periods of drought and low temperature. Two types of leaf seasonality can be distinguished: evergreen and deciduous. In the former, trees are in leaf throughout the year. While this leaf habit has the advantage of providing year-round photosynthesis, the leaves will suddenly die under conditions of extreme drought or low temperatures, which occasionally occurs in the study area. A deciduous leaf habit consists of a normal loss of leaves during drought or low temperatures. This type of habit can advantageously avoid sudden leaf death due to drought or freezing. However, it cannot provide photosynthesis throughout the year.

II. Types of Savanna Vegetation

In this study, a savanna is defined as having woody vegetation with a more or less discontinuous crown cover of trees that is greater than 5%. Woody vegetation characterized by a completely continuous cover corresponds to a forest, whereas desert is defined as vegetation having a crown cover of less than 5% (Fig. 2).

The various types of savanna are defined by a combination of the seasonality and leaf size of the vegetation: the deciduous type (Fig. 3, 4), the evergreen nanophyll type (Fig. 5), and the evergreen notophyll type (Fig. 6). In addition, deciduous nanophyll and deciduous notophyll types also arise by a combination

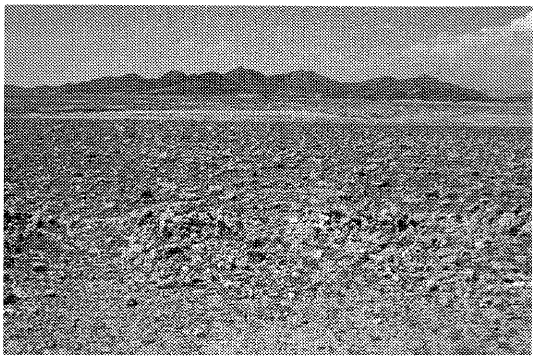

Fig. 2. Landscape of the Namib Desert near Gobabeb (west-central part of Namibia, 23° 42'S, 15°18'E). For the locarity of photograph, see Fig. 1.

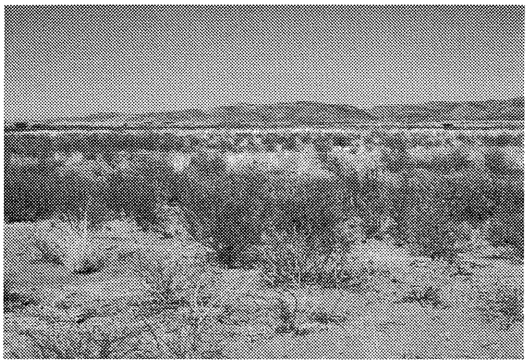

Fig. 3. Example of deciduous savanna near Maltahoehe (central part of Namibia, 24°01'S, 16°54'E). The maximum height of the vegetation is 4 m. The total woody vegetation cover is 25%. Deciduous trees completely dominate this area, accounting for 95% of the total woody cover. No evergreen notophyll trees are found. The herbaceous layer covers 40% of the ground. For the locality of photograph, see Fig. 1.

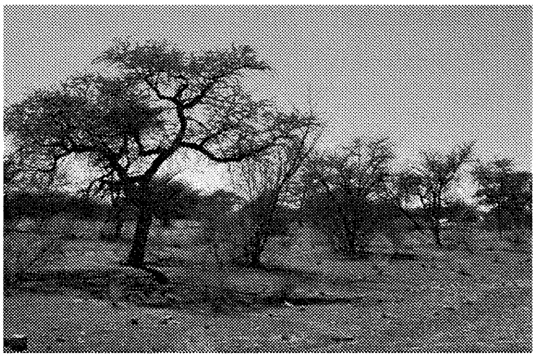

Fig. 4. Example of deciduous savanna near Gobabis (east-central part of Namibia, 23°02'S, 18°45'E). The maximum height of the vegetation is 8 m and the total woody vegetation cover is 80%. Deciduous woods dominate, accounting for 55% of the total woody cover, followed by evergreen nanophylls; evergreen notophylls rarely occur. The herbaceous layer covers 10% of the ground. For the locality of photograph, see Fig. 1.

Fig. 5. Example of evergreen nanophyll savanna near Tsumeb (northeastern most part of Namibia, 19°06'S, 18°37'E). The maximum height of the vegetation is 17 m, and the total woody vegetation cover is 150%. Evergreen nanophylls dominate, accounting for 60% of the total woody cover, followed by deciduous trees (25%) and evergreen nanophylls (15%). The herbaceous layer covers 15% of the ground. For the locality of photograph, see Fig. 1.

of leaf habits. However, these two types were not investigated in this study, because it was impossible to determine the leaf size of the deciduous trees based on field observations conducted at the end of the dry season.

The advantages of classifying savanna types according to leaf habit are that (1) the leaf habit directly indicates the ecological adaptation of the vegetation to the environment; (2) it is the most suitable indicator of factors controlling the different savanna types; and (3) more practically, it allows the factors controlling savanna types to be discussed on a phytogeographical basis, regardless of

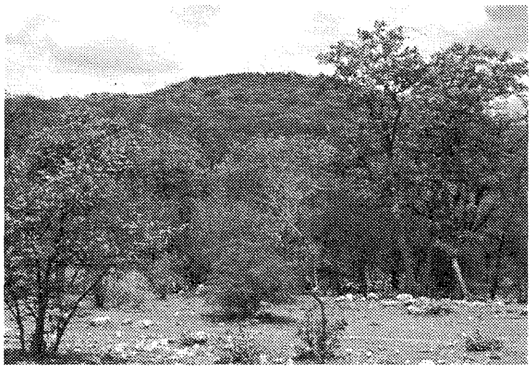

Fig. 6. Example of evergreen notophyll savanna near Opuwo (north-eastern-most part of Namibia, 17°26'S, 14°42'E). The maximum height of the vegetation is 19 m, and the total woody vegetation cover is 180%, similar to the value of typical forests. Evergreen notophylls dominate, accounting for 60% of the total woody cover, followed by evergreen nanophylls; deciduous trees are rare (7% of total woody cover). The herbaceous layer covers 30% of the ground. For the locality of photograph, see Fig. 1.

the taxonomic identification of the major wood species.

III. Field Observations

Field observations were carried out during three years (2001, 2002, 2003) at the end of the dry season (from the end of July to the beginning of November). The observations covered both the desert and the savanna, with the main focus on the savanna.

Plots along the major roads were selected in areas where the degree of human impact on vegetation was minor. Plots along rivers and seasonal streams were omitted to avoid the effects of exceptional water supply on the vegetation. I surveyed a total of 71 savanna plots. Plots that were not considered to represent savanna, i.e., desert plots, were all located in the Namib Desert.

In each savanna plot, the vegetation cover was measured by eye and classified into three layers: a tree layer, >5 m in height; a sub-tree layer, 2–5 m in height; and a shrub layer, <2 m in height. In addition, in each layer, the cover of each leaf habit, i.e., deciduous, evergreen nanophyll, and evergreen notophyll, was measured. In this study, the cover is expressed as the percent of the sum of the vertical projection of the crown within a layer. Accordingly, the maximum cover in each layer is 100%, and total woody cover, defined as the total sum of the cover of each layer, has a maximum value of 300%. Forests with a continuous crown cover generally have a total woody cover of more than 200%. The maximum height of the trees in each plot was also measured. The types of savanna in the plots were determined by the dominant leaf habit of the species that composed the highest percentage of the total woody cover. The amount of precipitation received by each plot was estimated from the distribution map of the annual precipitation of Namibia (Fig. 1).

RESULTS

I. Relationship between Annual Precipitation and Vegetation Performance

Figure 7 shows the relationship between the total woody vegetation cover and the annual precipitation of the plots. Total cover ranged from a minimum of 5%, characteristic value to savanna vegetation, to 220%, which is similar to the value typical of forests. In Namibia, savanna vegetation receives an annual

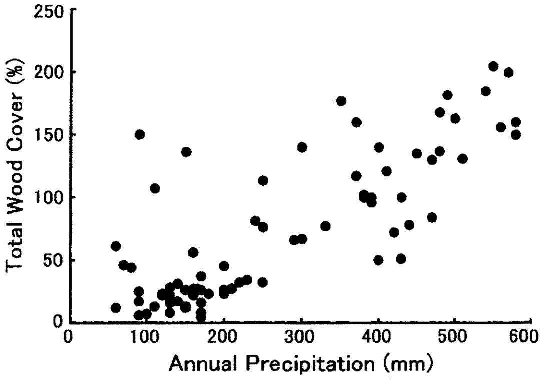

Fig. 7. Relationship between total woody vegetation cover and amount of annual precipitation in the plots.

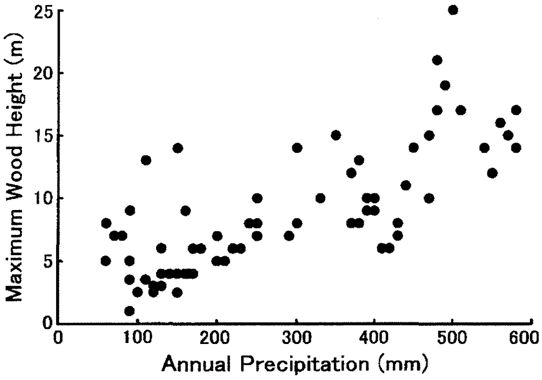

Fig. 8. Relationship between maximum wood height and amount of annual precipitation in the plots.

precipitation of 50 to 600 mm. Plots receiving less than 50 mm of precipitation always contained desert vegetation. The critical amount of precipitation in the transition from desert to savanna in Namibia is therefore ca. 50 mm.

The total vegetation cover was positively correlated with the amount of annual precipitation (Fig. 7), which increased incrementally but did not reach saturation, and barely attained the value of genuine forests in the study area. However, this relationship was not definitive since there was a relatively wide fluctuation in total cover despite similar amounts of precipitation; for example, the total cover of plots with 100 mm of precipitation ranged from 5–150%.

Figure 8 shows the relationship between the maximum tree height and annual precipitation received. The maximum tree height ranged from 1 m, the minimum value of savanna trees, to 25 m, which is similar to the value in typical forests. The maximum tree height was positively related to both the amount of annual precipitation and the total vegetation cover.

II. Relationship between precipitation and savanna type

Figure 9 shows the annual precipitation range for each savanna type and illustrates the fairly complete overlap. Annual precipitation ranged from 50 to 480 mm in the deciduous type, 70 to 600 mm in the evergreen nanophyll type, and 50 to 510 mm in the evergreen notophyll type. Annual precipitation was never the only factor controlling the occurrence of a particular savanna type.

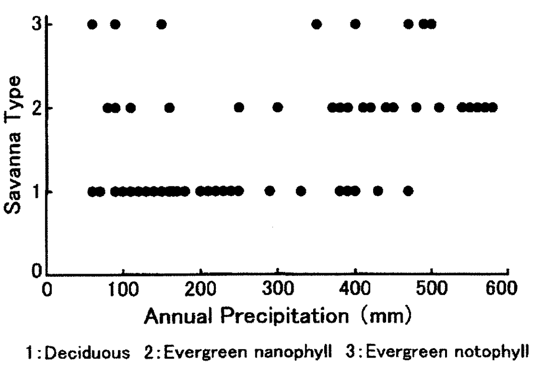

Fig. 9. Annual precipitation ranges in the three savanna types.

III. Geographical distribution of savanna types

Figure 10 illustrates the geographical distribution of the three savanna types according to physiographical regions and overlaid with the mopane areas in

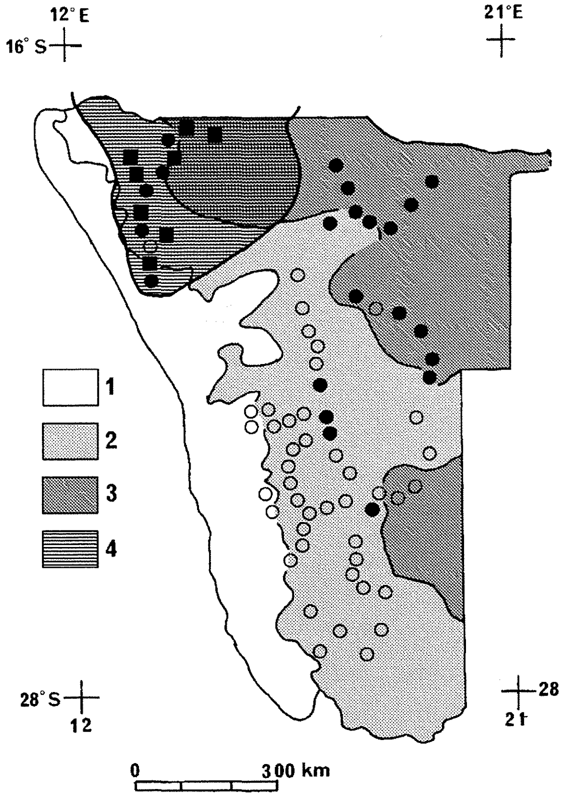

Fig. 10. Distribution of the three savanna types according to geographical region and area of mopane (*Colophospermum mopane*) in Namibia (after Okitsu, 2004b).
■ : Evergreen notophyll type, ● : Evergreen nanophyll type, ○ : Deciduous type.
1: Namib Desert, 2: Central Highland, 3: Mega Kalahari, 4: Distribution of mopane in Namibia, except in Kapribi (Palgrave, 1983).

Namibia. Table 2 quantitatively summarizes the frequency of the plots in each savanna type and in each physiographical region, including the mopane area. Only three plots in the Namib Desert had savanna vegetation; these were located on the border between the Namib Desert and the Central Highland. In contrast, in the Central Highland and Mega Kalahari, savanna vegetation occurred almost exclusively.

Of the 41 deciduous-type plots, 34 occurred in the Central Highland. There were also three plots in the Mega Kalahari, three in the Namib Desert, and one in the mopane area. The evergreen nanophyll type appeared primarily in the Mega Kalahari (12 plots), with fewer in the Central Highland (five plots) and in the mopane area (five plots). The evergreen notophyll type was concentrated exclusively in the mopane area (eight plots), and its distribution was independent of any physiographical region, such as Mega Kalahari, Central Highland, or Namib Desert (Fig. 10).

In an analysis based on physiographical region, the Namib Desert contained the least savanna vegetation (only three plots), while the Central Highland, where the deciduous type predominated (34 of 39 plots, the remainder being evergreen nanophyll type), had the most. The Mega Kalahari was dominated by the evergreen nanophyll type (12 plots), with a few occurrences of the deciduous type (three plots). The mopane area had every savanna type, with the majority being the evergreen notophyll type (eight of 14 plots).

Table 2. Distribution of savanna types in each physiographical region in Namibia, based on Fig. 10. The numbers in the table indicate the number of plots surveyed.

Savanna type	Physiographical region				Total
	Namib Desert	Central Highland	Mega Karahari	Mopane Area	
Deciduous	3	34	3	1	41
Evergreen nanophyll	0	5	12	5	22
Evergreen notophyll	0	0	0	8	8
Total	3	39	15	14	71

IV. Relationship between Vegetation Cover and amount of Precipitation in Each Savanna Type

Figure11 shows the relationship between total woody vegetation cover and amount of annual precipitation for each savanna type; the relationship differed for each of the three types. In the deciduous type, we observed a positive correlation between the total cover and the amount of annual precipitation. However, the total cover of deciduous savanna was the smallest of the three types, being at most 120% even in plots receiving more than 400 mm of annual precipitation. The evergreen nanophyll type showed the clearest relationship between total cover and annual precipitation. The total cover was lower (10–50%) in plots with less annual precipitation, around 100 mm, but higher (200%) in plots receiving more than 400 mm of annual precipitation. Evergreen notop-

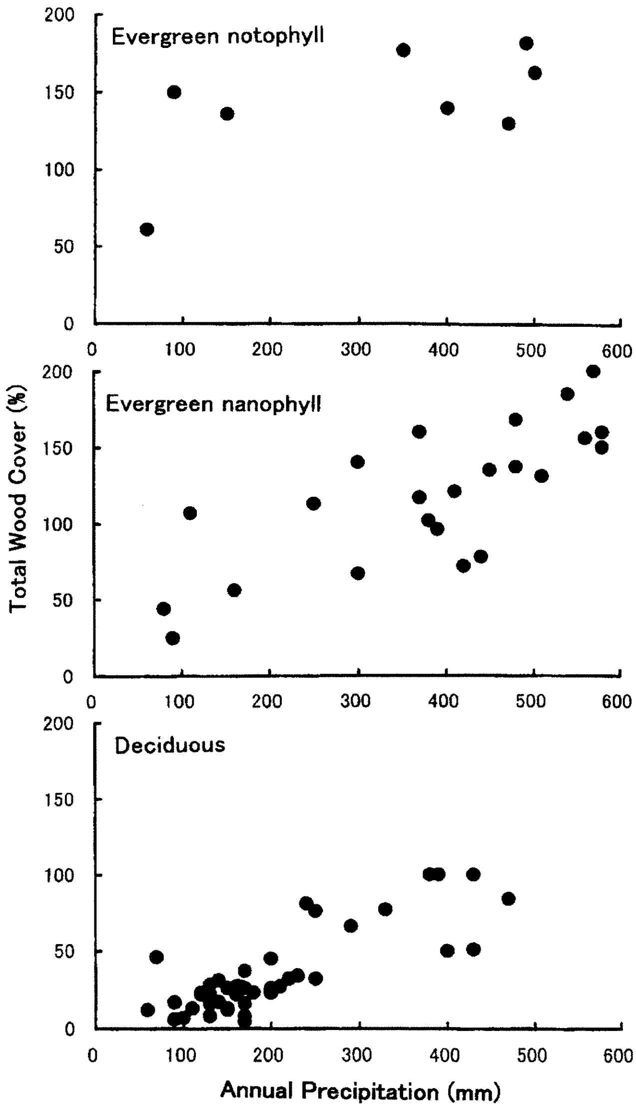

Fig. 11. Relationship between total woody vegetation cover and amount of annual precipitation in the three savanna types (after Okitsu, 2004b).

hyll savanna had the largest total cover of the three savanna types. Even in plots with the lowest amount of annual precipitation (70 mm), the total cover was as high as 60% and rapidly increased to 150% at 100 mm of annual precipitation before more slowly reaching 200% at 500 mm of annual precipitation.

DISCUSSION

I. Relationship between the Amount of Precipitation and the Occurrence of Savanna Vegetation and Tree Performance in Namibia

In Africa, savannas occur generally in regions where the amount of precipitation is less than 700 mm, while tropical forests are found in regions where precipitation is more than around 800 mm, although a broad transition exists between these regions (Okitsu, 2004a). The maximum amounts of precipitation measured in the savannas of Namibia are consistent with this definition. The minimum amount of annual precipitation measured in Namibian savanna is 50 mm, which is less than the amounts reported in other references, some of which documented ca. 100 mm (Cowling *et al.*, 1994; Archibold, 1995) or even ca. 200 mm (Knapp, 1973; Walter & Breckle, 1984; Juergens *et al.*, 1997; Rutherfold, 1997; Scholes, 1997). Despite these differences, the precipitation range in the Namibian savanna is within the general range measured in other parts of Africa.

Within the savanna, the amount of annual precipitation affects vegetation performance, which continuously increases with incremental increases in annual precipitation. Thus, the amount of annual precipitation scarcely attains the value required to sustain genuine forests in the study area, and it is not sufficient to promote additional, well-developed forests.

II. Factors Controlling the Occurrence of Savanna Types in Namibia

I expected that the occurrence of a particular savanna type would coincide with the amount of annual precipitation, such that the deciduous type would occur in areas with the lowest levels of annual precipitation, the evergreen nanophyll type would occur in intermediate areas, and the evergreen notophyll type would be found in areas receiving the most annual precipitation. In fact, however, the occurrence of a savanna type does not necessarily coincide with this expected pattern. Annual precipitation is not the sole factor controlling the occurrence of savanna type in Namibia, although it does account for the vegetation performance of the savanna as a whole.

Instead, the type of savanna is closely associated with the physiographical region in which it occurs. This suggests that the presence of each savanna type should correspond to the different environments of the physiographical regions, regardless of the amount of annual precipitation received. To identify the factors controlling the occurrence of each savanna type, the following sections mainly focus on the environments of the various physiographical regions and on the ecological characteristics of mopane.

1. *Deciduous savanna*

This type occurs mainly in the Central Highland, regardless of the amount of annual precipitation. Indeed, the Central Highland contains almost exclusively deciduous savanna, which strongly suggests that the environment of the Central Highland inevitably favors deciduous leaf habits. The water-holding capacity of the leptosols, the dominant soil type in this region, is low. Coupled with the highly undulating landforms, this can result in very high rates of water run-off and soil erosion. Furthermore, savanna vegetation in this region is always subject to extreme drought during the dry season. As a result, the xeric conditions of the soils during the dry season inevitably force the vegetation to maintain deciduous leaf habits.

Deciduous savanna consistently had the lowest total woody vegetation cover among the three savanna types despite similar amounts of annual precipitation. This can be explained by the fact that the deciduous leaf habits cannot support photosynthesis throughout the year, resulting in a lower photosynthetic production rate than can be achieved in trees with an evergreen leaf habit. In turn, this lower photosynthetic production rate may account for the lower total crown cover of deciduous savanna. Thus, the prevailing factor controlling the occurrence of this savanna type is the extremely dry soil condition during the dry season, which is due to the poor water-holding capacity of the soils, regardless of the amount of annual precipitation received. The sporadic incidence of deciduous savanna in the other physiographical regions may also result from the microtopographic occurrence of habitats with extremely dry soil conditions.

The total woody vegetation cover of deciduous savanna increased with increasing precipitation in the plots. This indicates that the amount of precipitation during the growing season significantly affects vegetation performance, in accordance with the general pattern.

2. *Evergreen nanophyll savanna*

The evergreen nanophyll type is found primarily in the Mega Kalahari. Conversely, the Mega Kalahari contains almost exclusively evergreen nanophyll savanna, suggesting that the environment of this region is conducive to this savanna type. The loose structure of the arenosols, associated with calcrete layers near the surface, as well as the flat plains and smooth hills of this region allow for little run-off of water. This implies that during the year, the soil never experiences a shortage of moisture, and the vegetation can therefore maintain an evergreen leaf habit. Thus, the prevailing factor controlling the occurrence of evergreen nanophyll savanna is primarily the moisture content capacity of the arenosols of this region, regardless of the total precipitation. The evergreen nanophyll type is also found in the Central Highland and in the mopane area. This may result from the occurrence in those regions of microhabitats suitable to evergreen nanophyll savanna.

However, the soil moisture conditions of the Mega Kalahari are insufficient for the vegetation to adopt a larger leaf size; the dominant leaf types in this region are nanophylls, which are smaller than notophylls. The water-holding capacity of the arenosols must be greater in order to maintain the larger leaf sizes characteristic of evergreen notophyll savanna.

I observed a clear relationship in the evergreen nanophyll savanna between total woody vegetation cover and amount of annual precipitation. The evergreen habitat allows for efficient use of the water supply present in the soil throughout the entire year. This continuous water use explains the strong correlation between total cover and amount of annual precipitation.

3. *Evergreen notophyll savanna*

The evergreen notophyll type is exclusively located in the mopane area, although the two other savanna types are also found there. Thus, the occurrence of evergreen notophyll savanna depends on the ecological nature of mopane itself, regardless of the amount of annual precipitation or the physiographical region.

Mopane is mainly found in the relatively flat and wide valley bottoms of large rivers and in the adjacent wide plains, at altitudes between 100 and 1,200 m. Mopane grows on fine-grained, sandy to loamy and clayey, usually deep soils (Werger & Coetzee, 1978). Soils in mopane areas tend to develop a high exchangeable sodium content (Kennedy & Potgieter, 2003).

The eastern range of the mopane area receives about 500 to 600 mm of annual precipitation, although farther west to the escarpment, annual precipitation drops to less than 100 mm (Fig. 1 and Fig. 10). This indicates that unlike other notophylls, which usually require large amounts of precipitation, mopane can tolerate extremely low amounts of moisture. The boundary of the mopane area in Namibia largely coincides with the 5°C isotherm of the mean daily minimum temperature for the coldest month, July (Werger & Coetzee, 1978).

The landform of the mopane area consists mainly of the wide flat Owambo Plain, at an altitude of about 1,100 mm, although the area principally belongs to the northernmost part of the Central Highland (Fig. 10). The soils of this area are dominated by the thick deposits of Kalahari sands (Erkkiae & Siiskonen, 1992). These environments are preferred by mopane.

Once mopane grows in a particular habitat, its large notophyll leaves are expected to attain higher rates of photosynthesis than nanophylls. Accordingly, evergreen notophyll savanna usually has a higher total woody vegetation cover than the other two types despite receiving similar amounts of precipitation. The total cover of the evergreen notophyll type is150%, even with annual precipitation reaching only 100 mm. Subsequently, with increasing precipitation, the total cover quickly increases, ultimately reaching around 200%. Thus, the decisive factor controlling the occurrence of evergreen notophyll savanna is undoubtedly the ecological nature of mopane, regardless of the amount of annual precipitation and the physiographical region. The mopane area includes both the Central

Highland and the Mega Kalahari. This regional variation provides microhabitats conducive to the occurrence of every type of savanna.

CONCLUSION

In Namibia, the amount of annual precipitation controls the general performance of the savanna vegetation, consistent with the generally accepted view. However, the geographical distribution of the three specific savanna types in Namibia is related to factors other than annual precipitation. One factor is the ability of the soil to retain moisture; this is closely associated with the change from deciduous to evergreen nanophyll savanna. The other factor is the ecological nature of mopane which is independent of physiographical region; this control the distribution of the evergreen notophyll type.

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OBSERVATION OF RIPARIAN VEGETATION IN WESTERN NAMIBIA BY USING NDVI AND NDWI DERIVED FROM SPOT-VEGETATION

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ABSTRACT Ephemeral rivers in western Namibia are unique entities that support both natural vegetation and human activities. This paper presents an approach for observing riparian vegetation along them synoptically using remotely sensed datasets, derived from a satellite borne sensor named SPOT-VEGETATION. The most commonly used vegetation index, the Normalized Difference Vegetation Index (NDVI), certainly delineates the overall distribution of vegetation, but not without errors. A vegetation index that was designed as a supplement for NDVI, the Normalized Difference Water Index (NDWI), showed some interesting features, but again, with faults. By synthesizing the two indices, the scarce and sparse vegetation in coastal deserts and the relatively dense vegetation in inland highlands could be efficiently observed. Furthermore, by introducing a flow accumulation model produced from a digital elevation model (DEM), it became possible to observe such riparian vegetation quantitatively and systematically.

Key Words: Riparian vegetation; Ephemeral rivers; Flow accumulation model; Namibia; Normalized Difference Vegetation Index; Normalized Difference Water Index; SPOT-VEGETATION.

INTRODUCTION

Ephemeral rivers in western Namibia are at the center of several natural and social scientific contexts. Geographically, they stretch westward from areas of relatively high rainfall, ranging between 300 and 600 mm per year (Jacobson *et al.*, 1995), to drier areas of 100 mm per year or less (Jacobson *et al.*, 2000). They may only fill up with water seasonally, or once every few (up to ten) years. Ecologically, they support riparian vegetation and provide intermittent water sources for fauna. Economically, they are critical resources for both agriculture and tourism development. In this arid region, water is of great importance, and hence, observation of ephemeral rivers and riparian vegetation along them is an important task for many communities.

OBJECTIVE OF STUDY

There are two ways to carry out observations of ephemeral rivers and riparian vegetation along them. One involves field observation, and the other synoptic observation; both have advantages and disadvantages. The objective of this study was to lay a foundation for synoptic observations of ephemeral rivers and their catchments by using datasets derived from a satellite sensor and a digital elevation model. This attempt could be of significance. The synoptic observation could function as a matrix to weave a number of individual field observations, which could in turn lead to a better understanding of the rivers and their catchments in the future.

STUDY AREA AND DATASETS

This study focuses on the ten catchments in western Namibia. Their sizes and shapes vary. They share, however, certain common features. The ephemeral rivers in them originate from inland mountains. Courses of the rivers towards the Atlantic Ocean correspond to the steep climatic gradients mentioned earlier: There is a contrast between the tributaries in the upper streams that are often moist and the mainstreams in the coastal deserts that are almost lastingly dry with very rare punctuations.

To observe the area synoptically, SPOT-VEGETATION (VGT) datasets having 1 km per pixel spatial resolution were used in this study. The particular type of the datasets used was called VGT-S10. It is a synthesized dataset in which cloud free pixels are compiled from scenes of the area of interest acquired over ten days. The synthesized data sets, S-10, consisted of four spectral bands and pre-processed Normalized Difference Vegetation Index (NDVI). In the preparatory stage, 36 sequential S-10 datasets from April 1998 to March 1999 were acquired. From these scenes, the rectangular area containing Namibia was cropped. GTOPO 30 Digital Elevation Model (DEM) having 1 km spatial resolution was also used in this study. Two tiles of the global DEM were combined together, and the relevant area was extracted.

PARAMETERS

Two parameters were used in this study for characterizations of vegetation along the ephemeral rivers and in their catchments. One of these was NDVI. This parameter indicates vigor of vegetation by taking advantage of its spectral characteristics: While vegetation absorbs electromagnetic radiation in the visible region, it reflects that in the near-infrared region; and, the absorption and reflectance can be measured and the difference calculated.

An important point to note is that although they are called 'rivers', ephemeral rivers are essentially exposed riverbeds. This means that what to observe is not actual water, but the results of occasional water. In this context, riparian vegetation is a relevant medium.

A further consideration was required in this study. As the rivers and their catchments were in an arid area, sole reliance on NDVI for observation of vegetation might not be appropriate. To ameliorate this uncertainty, another parameter, the Normalized Difference Water Index (NDWI) was introduced to this study. This parameter indicates the moisture content of vegetation (Gao, 1996). In other words, it is better used as a supplement to NDVI (*ibid.*). This parameter was not readily available, and therefore computed from the spectral bands of SPOT-VEGETATION as Xiao *et al.* (2002) did in a previous study. Later in this paper, what these two parameters indicated are examined first, and an attempt to combine them together is made.

EXTRACTION OF WATERSHEDS FROM DIGITAL ELEVATION MODEL

A series of terrain analysis procedures were applied to the prepared DEM. Two raster layers were produced from this phase. One of these was a flow accumulation layer, indicating how water flows down the terrain. The other layer indicated watersheds, more specifically, sub-watersheds that comprise the catchments defined by Jacobson *et al.*, (1995). The small watersheds were combined together until the outline of the catchments (*ibid.*) appeared. After this integration process, the catchments were vectorized. The original elevation model prepared for this study and the consequent datasets were used in conjunction with the two parameters explained earlier.

SEASONAL AMPLITUDES OF VGT-NDVI

Vegetation vigor for one year was observed and a number of useful points were found. The first operation was a further maximization of the cropped S-10 NDVI dataset. This transformed the 10-day NDVI MVC (maximum value composite) dataset consisting of 36 images into a monthly NDVI MVC dataset consisting of 12 images.

The second operation was an unsupervised classification procedure. The ISODATA algorithm (Tou & Gonzalez 1974) was used for the monthly VGT-NDVI MVC dataset to group pixels having same patterns of seasonal fluctuation. Fig. 1 shows the results, and Fig. 2 shows the monthly mean VGT-NDVI of each class area. These should not be taken as a definitive segmentation of vegetation in the area. While there was a likely correlation between the output of our classification procedure and various aspects of vegetation, such as species, formation, or density, the purpose of the operation was to produce a probe to further the analysis on the riparian vegetation. The number of classes, nine, was determined solely for visualization purposes.

The results of the classification operation provided a number of useful points. Firstly, the concordance between the spatial distribution of the classes (Fig. 1) and their chronological fluctuations (Fig. 2) is remarkable. Amplitudes of VGT-NDVI values of upstream areas are generally larger than those of downstream areas. There is a gradation of VGT-NDVI between inland highlands and coastal deserts. Secondly, in relation to the first point, durations that VGT-NDVI

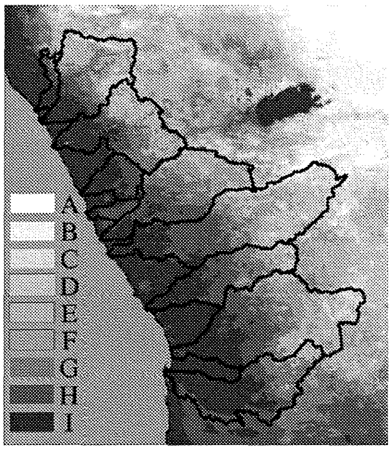

Fig. 1. Nine classes resulted from the ISODATA classification.

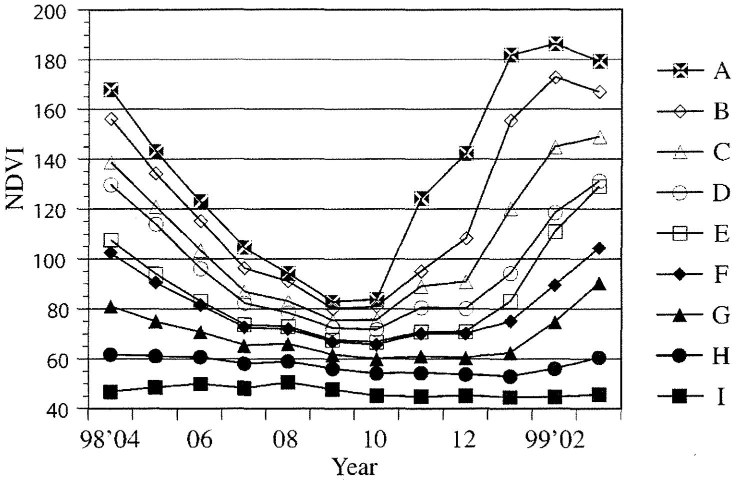

Fig. 2. Monthly changes of mean VGT-NDVI of the classes.

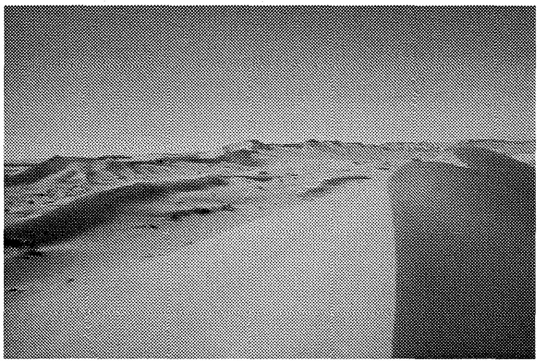

Fig. 3. The Namib Sand Sea.

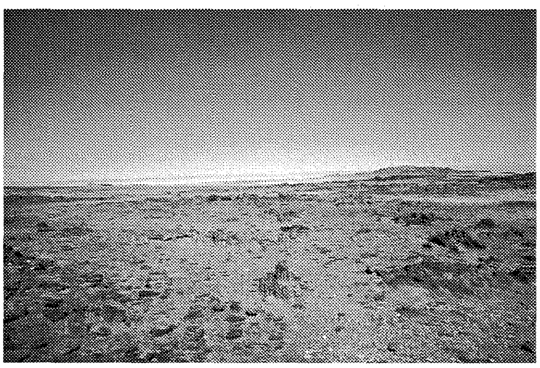

Fig. 4. Coastal Desert.

values of the upstream areas stay low are shorter than those of the downstream areas. Thirdly, and possibly most importantly in the context of this study, the Namib Sand Sea in the south of the Kuiseb catchment was in the class H area. The sand sea shown as Fig. 3 is as scarcely vegetated as the class I areas of which example is shown as Fig. 4. This point implies delimitation of sole reliance on VGT-NDVI in observations of such arid areas.

SEASONAL AMPLITUDES OF VGT-NDWI

It is of considerable interest to examine fluctuations of VGT-NDWI. Fig. 5 shows the monthly mean VGT-NDWI in areas defined by the ISODATA classification operation applied to the sequential VGT-NDVI dataset. When comparing Fig. 2 and 5, the following three points should be noted. Firstly, similar to the behavior of the monthly VGT-NDVI, VGT-NDWI of the upstream areas had larger amplitudes and stayed low for a shorter duration than in the downstream areas. Secondly, unlike those of the VGT-NDVI, VGT-NDWI of the upstream areas became even lower than that of the downstream areas and the Etosha Pan

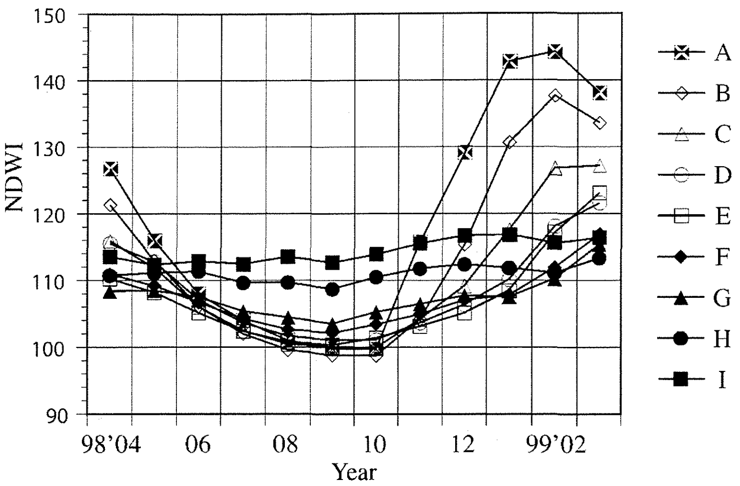

Fig. 5. Monthly changes of mean VGT-NDWI of the classes.

from June to November. Thirdly, and most strikingly, coastal desert areas (Fig. 3 & 4) and the Etosha Pan retained a certain level of VGT-NDWI throughout the one-year period.

The similarities and differences between fluctuations of VGT-NDVI and VGT-NDWI values, as well as being interesting issues in themselves, provide useful clues for further data processing in this study. Probable explanations for the unexpected behaviors of the VGT-NDWI are that:

1) NDWI was designed originally to measure the moisture of vegetation, but not of soil;
2) The coastal desert areas and the Etosha Pan coincidentally had spectral characteristics similar to moderately moist vegetation; and
3) VGT-NDWI of scarce or dense vegetation in inland areas exceeded the 'quasi moisture' of soil background as the dry season ended and the rainy season started.

This explains the sequential turns depicted in Fig. 5; it also implies delimitation of sole reliance on VGT-NDWI.

SYNTHESIS OF THE TWO PARAMETERS

The two parameters having been examined so far are usefully indicative of vegetation conditions in the catchments but not entirely free from error. It is, then, sensible to combine them together. A gambit to find a way to synthesize the two parameters is to produce a two dimensional feature space by using them as the axes. The two graphs, Fig. 2 and 5, can be combined in such a feature space. The seasonal trajectories of the classes, which are determined by VGT-NDVI and VGT-NDWI, can be represented as a scatter plot shown in Fig. 6.

This graphical representation of vegetation conditions of the area leads to a number of noteworthy points. Most notably, it implies that:

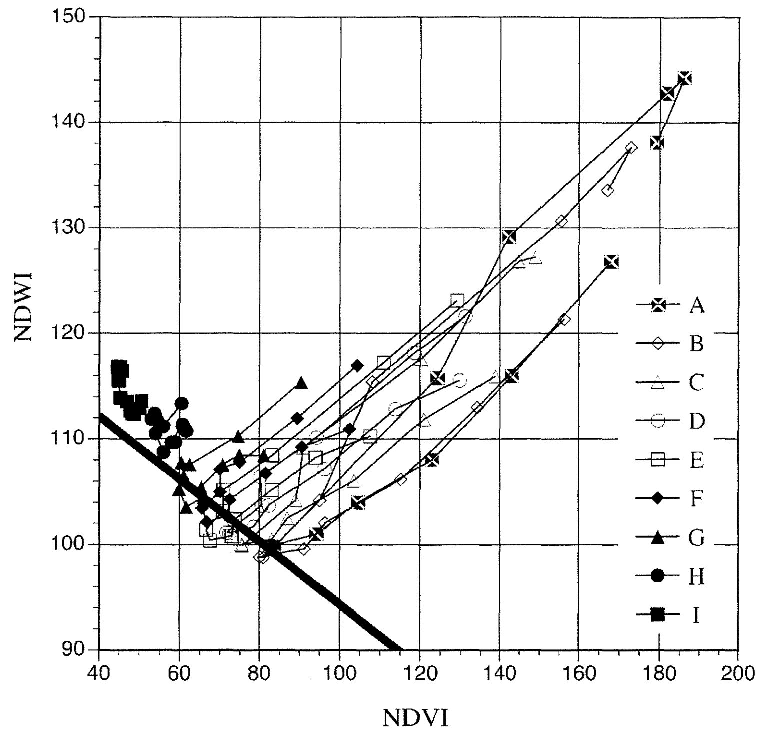

Fig. 6. Scatterline plot.
Monthly mean VGT-NDVI (X) and VGT-NDWI (Y) values of the classes.

1) The lowest (i.e. bottom left) coordinates of all seasonal trajectories were from September VGT-NDVI and VGT-NDWI images, and aligned along a diagonally downward line from left to right in the feature space; and
2) Amplitudes of trajectories, the distance between the bottom left coordinate and the top right coordinate, for coastal areas were smaller than those for inland highlands.

In short, the amplitudes of the trajectories were inversely proportional to the coordinate values determined by the driest month, September.

A straightforward way to take advantage of the above points to synthesize the two parameters was to calculate the magnitude of seasonal trajectory that each pixel had. This could be an appropriate indicator for what the Namibian ephemeral rivers go through and how they function. An image as a compilation of such pixels was produced through the following image arithmetic:

$$Amplitude = \sqrt{(NDVI_2 - NDVI_1)^2 + (NDWI_2 - NDWI_1)^2}$$

where $NDVI_1$, $NDVI_2$, $NDWI_1$ and $NDWI_2$ were the VGT-NDVI and VGT-NDWI images in September 1998 and March 1999 respectively. The resultant two-dimensional amplitudal image, shown in Fig. 7, indicates the distances between coordinates determined by the two parameters in September 1998 and those by the parameters in March 1999. This approach may be comparable to that of Malila (1980), Kajiwara and Tateishi (1990), and Lambin and Strahler (1994a, b), whereby the researchers carried out 'change vector analysis.' A difference

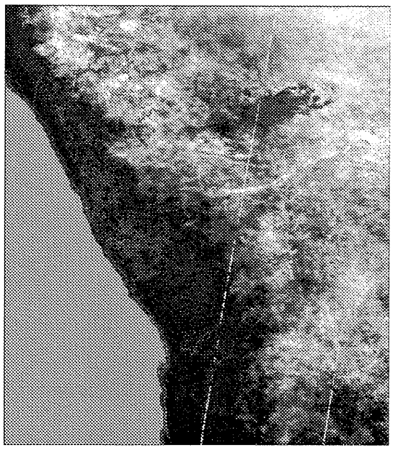

Fig. 7. Two dimensional amplitudal image.

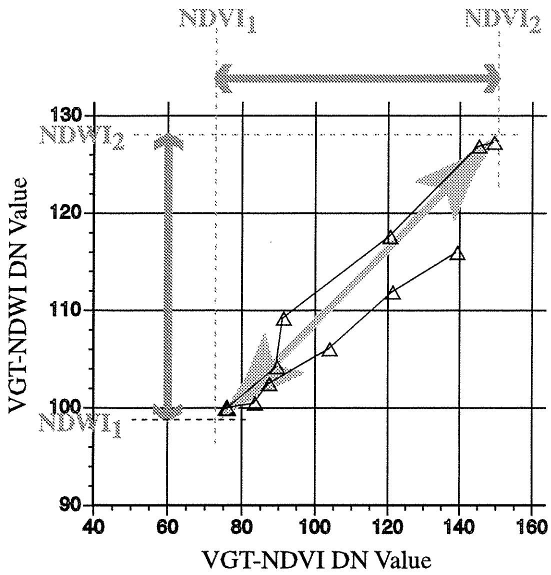

Fig. 8. Scatterline plot.
Two-dimensional amplitude — VGT-NDVI (X) and VGT-NDWI (Y)

between them and the above operation is that while two spectral bands were used in the formers, two indices were used in the latter.

The two-dimensional amplitudal image had a distinctive characteristic as compared to the VGT-NDVI and VGT-NDWI. The length of the two-dimensional amplitudal vector was longer than either of the two parameters, as shown in Fig. 8. This characteristic could be useful in observations of vegetation conditions along ephemeral rivers and in their catchments.

OBSERVATIONS OF RIPARIAN VEGETATION

The approach having been explained so far produced a matrix for spatiotemporal analyses of the Namibian riparian vegetation. The potential was more effectively exploited through introduction of the DEM. The first step in utilization of the DEM was production of a flow accumulation model. A DEM consists of pixels indicating altitude of corresponding areas. It is, then, possible to estimate how surface waters as streams converge and rivers run through valleys and plains if a set of relevant algorithms are applied to the DEM. This operation was carried out and the resultant flow accumulation model is shown in Fig. 9. For better visual presentation, darkness/lightness of the mainstreams are differentiated from that of the tributaries.

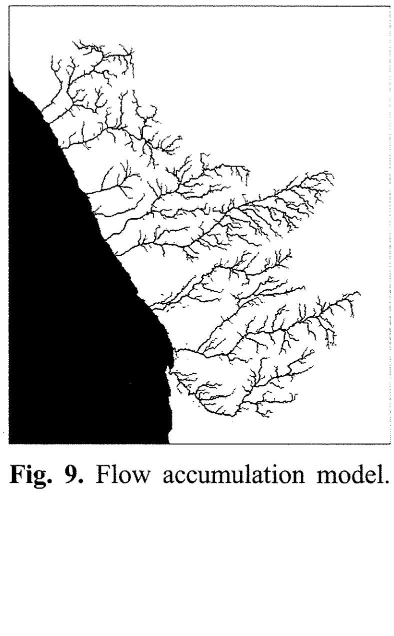

Fig. 9. Flow accumulation model.

The flow accumulation model is hypothetical. It is not definitive in the sense that the ground is

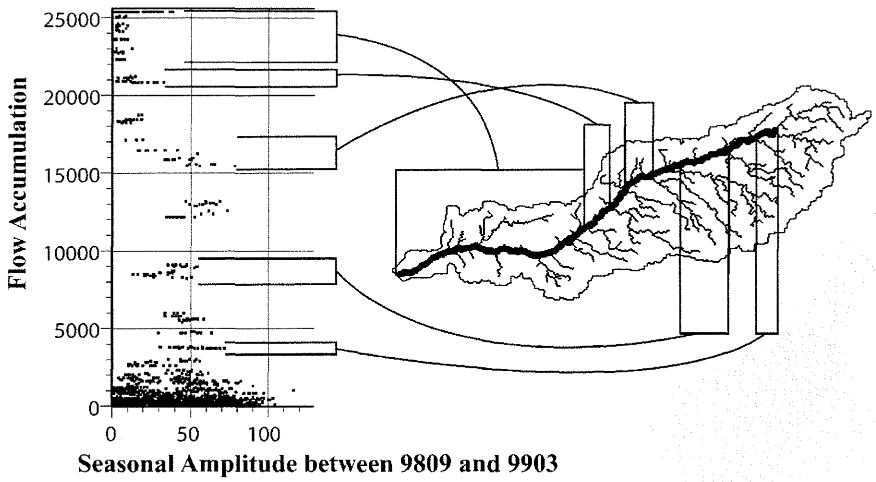

Fig. 10. Two-dimensional seasonal amplitude of the Ugab River.

rarely impermeable, precipitation tends to be uneven over a large area, and there is continuous evaporation from the surface of rivers and streams. In reality, the amount of water that is held by rivers and streams is highly likely to be different from that indicated by a flow accumulation model. It is, however, still a useful summary of catchments and a practical method for delineating probable watercourses. In the case of western Namibia, the model could be remarkably useful when determining how precious rainfalls are transformed into water flows and how they influence vegetation.

The second step was a modification of the flow accumulation model. The model indicated how much water was accumulated, theoretically, at each pixel. By imposing a threshold, the water courses could be more clearly expressed. In this study, the threshold was set to 100. This value produced lines through which water runs, accumulated from areas larger than 100 sq·km, and it omitted minor tributaries. After this operation, the flow accumulation values of the rivers were divided by 100 just to fit the range of the value to a relevant scale for calculation.

A series of scatter plot were produced by combining the modified flow accumulation model and the two dimensional amplitudal image. More concretely, river specific feature spaces were produced by assigning the former to the Y axis and the latter to the X axis. A scatter plot made for the Ugab catchment by using this method is shown as Fig. 10. This diagram also indicates which range on the Y-axis corresponds to which part of the Ugab River. Tributaries of the river were distributed over both coastal desert and vegetated highlands: They are represented as an agglomeration, having a wide range of X values and low Y values. As the flow accumulation value of the river increases (i.e., above the region of the agglomeration at the bottom), the X value decreases slightly, and increases again. In the coastal desert, the X value becomes extremely low, but shows a sudden increase at the Y value 21000. This increase was highly likely due to water inflow from nearby mountains.

It is also possible to produce sequential scatter plots to observe the

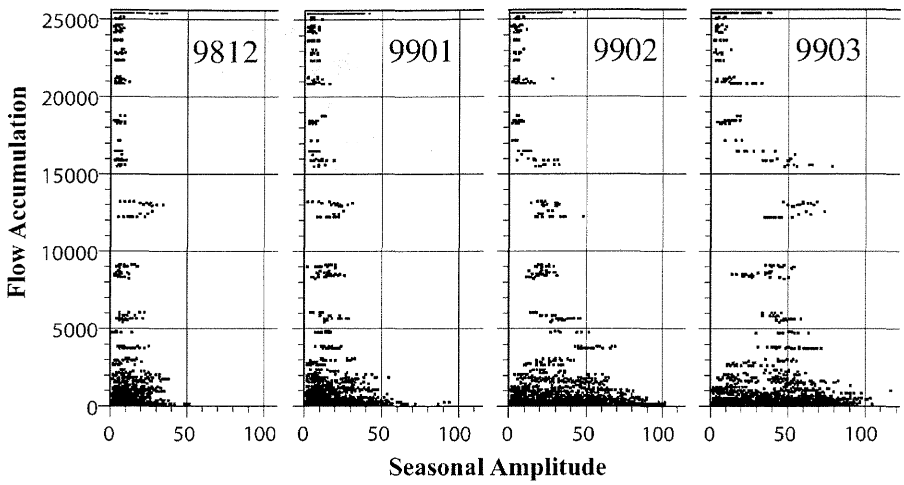

Fig. 11. Seasonal fluctuations of two-dimensional amplitudal value for the Ugab River.

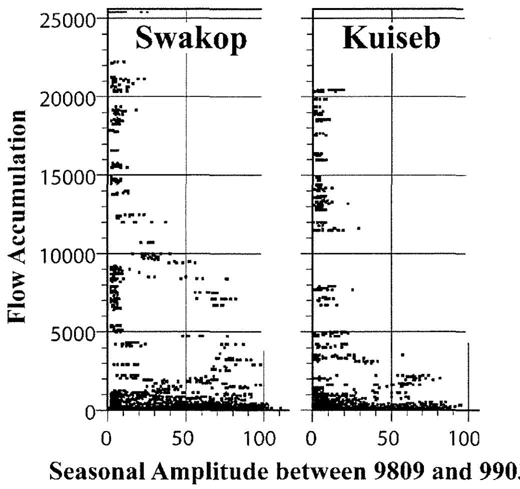

Fig. 12. Characterization of the drainage networks: Swakop and Kuiseb.

seasonality of the riparian vegetation. In addition to the data in Fig. 10, which features the difference between September 1998 and March 1999, differences between the former and other months could be observed as shown in Fig. 11. It is remarkable that the part of the river of which the Y value range is between 15000 and 18000 showed a dramatic increase in the X value in the period between February and March 1999. Such a feature could be useful for further research and field observation.

The same approach can be used for comparison of vegetation conditions along the ephemeral rivers. For example, Fig. 12 shows a comparison of the Swakop and Kuiseb Rivers. The diagram for the Swakop River features a ring-like shape. The shape was formed because the downstream of the Khan River was without much vegetation and the upstream of the Swakop River had relatively dense vegetation with the same Y value, and the two rivers joined in the coastal desert. Without the part of the upstream Swakop River, the two diagrams in Fig. 12 would look more similar. The diagram of the Kuiseb River has its own uniqueness; it has a few stray vegetated dots in the Y value range between 5000 and 15000. These were highly likely to be riparian vegetation that would look like oases on the ground. Both diagrams show increases of the X value at the river mouths (i.e., the top ends). These were probably due to vegetation in the two large coastal cities: Swakopmund at the mouth of the Swakop River, and Walvis Bay at the mouth of the Kuiseb River.

CONCLUSIONS

The approach explained in this study has demonstrated a way to observe synoptically vegetation along the ephemeral rivers and in their catchments in Western Namibia. It remains only an approach at present. It could be, however, developed further to function as a foundation for holistic comprehension of arid/semi-arid environments that would set individual field observations in relevant contexts. As development issues, such as the constructions of dams for agricultural water management or the expansion of the tourism industry, grow in importance, western Namibia needs a strong foundation for synoptic environmental comprehension. Future research scopes held from the achievements of this study comprise introduction of higher spatial resolution data sets for observations of areas of special interests and hyper spectral data sets for further investigation of the relationship between the rivers and vegetation covers.

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CLIMATE ANOMALIES AND EXTREME EVENTS IN AFRICA IN 2003, INCLUDING HEAVY RAINS AND FLOODS THAT OCCURRED DURING NORTHERN HEMISPHERE SUMMER

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ABSTRACT The climate of 2003, particularly during Northern Hemisphere summer, was marked by exceptionally abnormal events throughout the world, and Africa was no exception. As record heat waves prevailed over Europe, heavy rains and floods occurred over the west-central Sahara, across the Sudano-Sahelian region and western Kenya, while drought conditions gripped the Guinea Coast and southeastern Southern Africa, and cold waves hit southern South Africa. Among the most remarkable events were record rainfall in the western portion of the Sahara-Sahel and drought conditions over the Guinea Coast that were both caused by an extreme northward penetration of the ITCZ relative to normal years. In addition, record-breaking cold weather occurred in southern South Africa in mid-August by a strong extratropical cyclone accompanied by a cold front. During Southern Hemisphere summer, Madagascar, Mozambique, Zimbabwe, and Malawi frequently experienced heavy rains and floods associated with tropical cyclones and their remnants. More than 550 people died and over 2.5 million were displaced because of floods in Africa in 2003. Africa's vulnerability to climate hazards could be reduced through enhancements of both short- and long-term coping strategies, climate monitoring and early warning systems, flood control infrastructures, and other disaster preparedness measures at all levels, including sub-regional, national, and local levels. Mechanisms that caused various events in Africa in 2003, events which can be viewed as regional responses in Africa to anthropogenic global warming, must be explored from the perspective of global change.

Key Words: Climate anomalies; Extreme events; Heavy rains; Floods; Northern Hemisphere summer 2003.

INTRODUCTION

Ample evidence suggests that ongoing anthropogenic global warming has recently increased the frequency and magnitude of many extreme climate events, including floods, droughts, tropical and other storms, anomalous temperatures, and fires (IPCC, 2001b). The African continent is particularly vulnerable to climate change because of widespread poverty, recurrent droughts, inequitable land distribution, and overdependence on rain-fed agriculture (IPCC, 2001a). In many African countries, adverse effects from climate anomalies and events such as severe droughts or floods have increasingly threatened food security and human lives. Arid, semi-arid, and dry subhumid areas, which are collectively defined as "drylands," are particularly vulnerable to climate anomalies and events. This is best exemplified by the effects of persistent, severe droughts in the Sudano-Sahelian region south of the Sahara from the late 1960s to the early 1990s, and of ENSO (El Nino Southern Oscillation)-related significant droughts and/or floods that occurred over the Horn of Africa, equatorial East Africa, and southeastern Southern Africa in the 1980s and 1990s.

Onset of El Nino conditions from November 1997 to January 1998 in the equatorial Pacific Ocean was associated with abnormally wet conditions over the drylands of the Horn of Africa and equatorial East Africa (Fig. 1a), with outbreaks of rift valley fever in flood-stricken areas. During the same period, most of southeastern Africa experienced severe drought and food shortages. In contrast, during the 1999-2000 La Nina event subsequent to the 1997-98 El Nino, climatic conditions reversed. Conditions were drier than normal over the Horn of Africa and equatorial East Africa, and wetter over Southern Africa with powerful tropical cyclones accompanied by unusually heavy rains and extreme floods (Fig. 1b).

Persistent rains in February 2000 coupled with extremely heavy rains (250-500 mm) associated with Tropical Cyclone Eline pushed monthly rainfall to 350-1,000 mm, or 500-1,000% of normal, in southern Mozambique, northeastern Botswana, and South Africa. Record flooding ensued downstream of the Limpopo and Zambezi rivers (South African Weather Bureau, 2000; Fig 1b). Remnants of Eline traversed the sub-continent, reaching central Namibia where torrential rains caused flash floods in ephemeral desert rivers. These climate anomalies that have repeated almost every year have caused severe crop shortages in most countries from the Horn of Africa to Southern Africa. The total population at risk for food shortages was 20 million or more in some years.

During 2003, although no distinct El Nino conditions were present in the

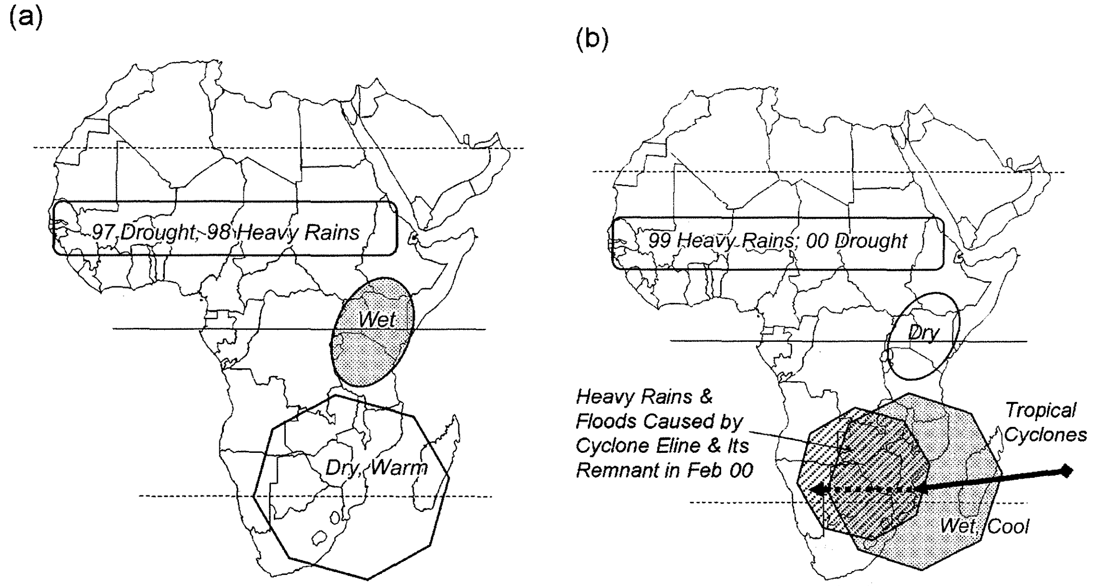

Fig.1. Significant climate anomalies and extreme events in Africa during the most recent ENSO years.
(a) 1997/98 El Nino (warm) years (Data from IPCC, 2001a; NOAA/CPC, 2002a; UNEP, 2002).
(b) 1999/2000 La Nina (cold) years (Data from IPCC, 2001a; NOAA/CPC, 1999, 2000, 2002b; UNEP, 2002).

equatorial Pacific Ocean, severe climate anomalies occurred throughout the world with heat waves and droughts in Europe and Canada, and a cool summer and heavy rains in Japan (NOAA/NCDC, 2004). In particular, during Northern Hemisphere summer from June through August 2003, Europe experienced heat unprecedented since 1500 (Luterbacher *et al.*, 2004) under the influence of a hot, dry ridge, which was associated with the subtropical Azores Anticyclone that stalled over Southern Europe. The death toll due to heat exceeded 35,000. Water shortages, forest fires, food crop failures, permafrost melting in the Alps, and other disastrous events occurred over Western Europe. The human toll of the heat wave was most severe in France, where 14,802 died (Earth Policy Institute, 2003). Weather in Africa was also unusual during this period. Heavy rains and floods occurred over the Sudano-Sahelian region and over equatorial East Africa, droughts plagued the Guinea Coast, and droughts and cold waves affected South Africa. (NOAA/NCDC, 2004).

This paper investigates climate anomalies and extreme events that occurred in 2003 across Africa, with an emphasis on rainfall anomalies and significant flood events during Northern Hemisphere summer, to serve as a basis for Africa-wide climate/environmental change studies. Data used in this study originated mostly from web pages published by the Dartmouth Flood Observatory, FEWS NET/ USAID (Famine Early Warning System Network/U.S. Agency for International Development), NOAA/CPC (National Oceanic and Atmospheric Administration/ Climate Prediction Center), NOAA/NCDC (NOAA/National Climatic Data Center), ReliefWeb, South African Weather Service, and vf-tropi.com.

CLIMATE ANOMALIES AND EXTREME EVENTS DURING NORTHERN HEMISPHERE SUMMER (JUNE-SEPTEMBER) 2003

I. Northern Hemisphere Africa

1) Western Parts of the Sudano-Sahelian Region and the Sahara

Beginning in early June 2003, the Intertropical Convergence Zone (ITCZ) in northern hemispheric Africa and the attendant rainbelt of heavy showers moved markedly northward (Fig. 2) into the Sudano-Sahelian region. The mean position of the ITCZ reached its normal northernmost extreme in mid-July, almost one month early (FEWS NET, 2003a). The ITCZ continued moving northward, reaching 20.5°N in mid-August, about 1.4° north of the normal extreme climatological position (FEWS NET, 2003d; French, 2003a, b). Because the ITCZ was unusually far north, there was enhanced rainfall in regions between 10°N and the Sahara Desert, and reduced rainfall with locally severe drought over coastal regions of the Gulf of Guinea (Figs. 2, 3a).

Convective activity was excited by the combined effects of the African easterly wave located near 15°N and deep, moist maritime air flow that characterized the Guinea Monsoon. As a result, localized heavy rains and floods were common in the Sudano-Sahelian region from Senegal in the west to Sudan and

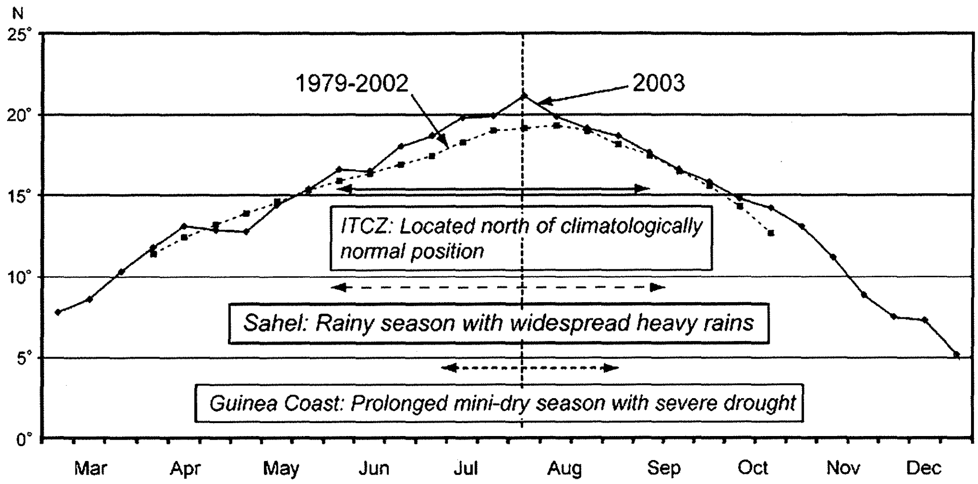

Fig. 2. Mean position of the ITCZ in West Africa 10°W-10°E from May-December 2003 in comparison of the long-term mean, with comments on rainfall anomalies in the Sahel and the Guinea Coast regions during the Northern Hemisphere summer season highlighted (Modified from NOAA/CPC, 2003).

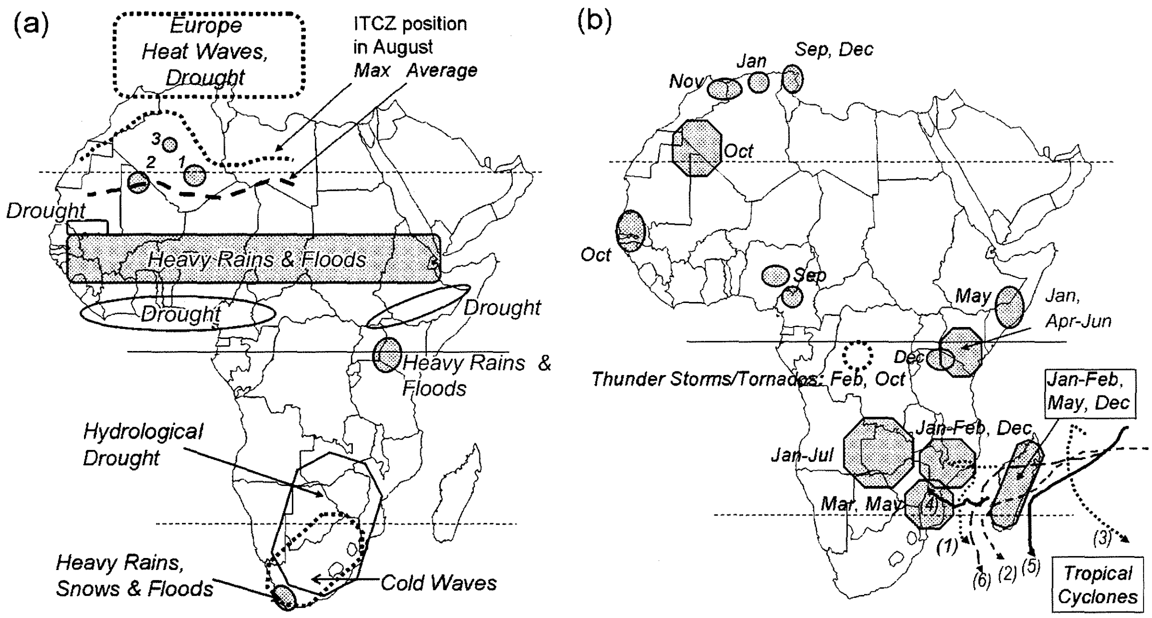

Fig. 3. Significant climate anomalies and extreme events in Africa in 2003.

(a) Significant climate events in August 2003 (Data from DFO, 2003; FEWS NET, 2003a, 2003b, 2003c, 2003d, 2003e, 2003f; NOAA/NCDC, 2004; ReliefWeb, 2003c, 2003d; South African Weather Service, 2003a, 2003b). 1: Tamanrasset; 2: Taoudenni; 3: Reggane.

(b) Heavy rains and floods in other months in 2003 with tracks of tropical cyclones (Data from DFO, 2003; FEWS NET, 2003g, 2003h; JAXA/EORC, 2003; NOAA/CPC, 2004; ReliefWeb, 2003a, 2003b, 2003c, 2003d, 2003e, 2003f, 2003g). Tracks of tropical cyclones–(1) Delfina: 30 December 2002-9 January 2003; (2) Fari: 23-30 January, 2003; (3) Gerry: 8-15 February, 2003; (4) Japhet: 26 February 03 March, 2003; (5) Manou: 3-10 May, 2003; (6) Cela: 5-21 December, 2003.

Eritrea/Ethiopia in the east (Fig. 3a). On 10-11 August, when the ITCZ reached its extreme northward extent, near 30°N (AGRHYMET, 2003; Fig. 4b), localized torrential rains fell and floods occurred over the western central Sahara,

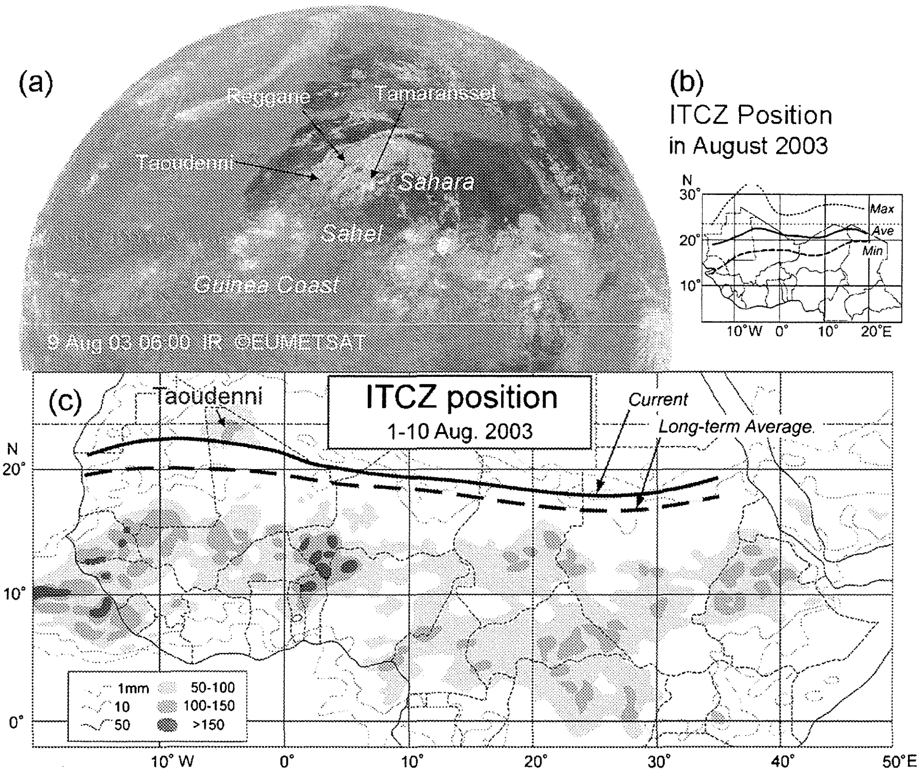

Fig. 4. ITCZ positions and heavy rains during the first decade of August 2003 in Northern Hemisphere Africa.

(a) METEOSAT infrared image on 9 August 2003 at 6:00 UTC showing spotty heavy rains over the Central Sahara and across the Sahel region (Copyright ©2003 EUMETSAT; EUMETSAT, 2003a).

(b) The maximum, average, and minimum positions of the ITCZ in August 2003 in West Africa (Modified from AGRHYMET, 2003).

(c) The 1-10 August 2003 and the long-term average 1-10 August ITCZ positions, and NOAA/NDVI-derived decadal rainfall estimates for 1-10 August 2003 (Modified from NOAA/CPC, 2003). Note that widely scattered heavy rains of more than 100 mm across the Sahel region and spotty heavy rains over the west-central part of the Sahara around Taoudenni, northern Mali. In contrast, the Guinea Coast region from Liberia to Ghana was under the condition of severe dryness.

especially over areas around Tamanrasset (22°42′N) in the Hoggar Mountains and Reggane Basin (26°43′N) in central Algeria (DFO, 2003; Figs. 3a, 4a, 4c). The Tomonian district 480 km east of Bamako, Mali, saw unusually heavy rains on 10 August, with 117 mm in a single day. That rain destroyed more than 700 grain storehouses and flooded 1,800 houses (ReliefWeb, 2003d).

As the ITCZ moved to the south after mid-August, the belt of heavy rains shifted to the Sudanian zone. Heavy rains fell from late August to early September around Kaduna in central Nigeria (Fig. 3b), leading to large-scale over-the-bank flooding on the Kaduna River, a tributary of the Niger River on 7 September (ReliefWeb, 2003e, f). More than 2,000 properties were destroyed and about 2,500 families were made homeless (Table 1). During September and October, 200,000 people in Nigeria were displaced because of flooding on the Niger River and its major tributaries, and the Hadejia and Jamaare Rivers, which are tributaries of the Komadougou Yobe River flowing into Lake Chad

Table 1. Main damages from heavy rains and floods in the Sudano-Sahelian countries during July-September 2003.

Country	Reported major damages.
Mauritania	3,600 houses destroyed and 21,000 homeless.[1]
Senegal	8 dead and 5,300 homeless.[1]
Mali	10,000 lost their homes in Bamako.[1] At least 180 ancient mud buildings on the World Heritage List destroyed in Timbuktu[2]
Burkina Faso	10 major towns flooded, 900 homes destroyed, and 3,000 families affected.[1]
Niger	7 dead, 1,000 homes destroyed, and 5,400 families affected.[1]
Nigeria	Over 2,000 properties destroyed, 3,600 homeless, and 10,600 displaced in Kaduna area.[3]
Sudan and Eritrea	79% of city area flooded and 80% of population homeless in Kassala, eastern Sudan. 20 dead and 325,000 displaced during 28 July–21 August in Sudan and Eritrea.[4]

Data from: (1) ReliefWeb, 2003c; (2) BBC, 2003; (3) ReliefWeb, 2003d, 2003e; (4) DFO, 2003.

in Jigawa State (DFO, 2003). Damage along the Kaduna, the Hadejia, and the Jamaare Rivers was aggravated by dam-released floodwaters. Similar events occurred along the upper stretches of the Benue River, a major tributary of the Niger River; 300 houses were washed away in a flash flood caused by discharge from Lagdo Dam in northern Cameroon.

Flood levels peaked in mid-September along the middle reaches of the Niger River: 10,000 people lost their homes in Bamako, the capital of Mali that is on the banks of the Niger River (Table 1). In Timbuktu, Mali, which is also on the Niger River, historic mud-built buildings on UNESCO's World Cultural Heritage List were threatened by flooding, and at least 180 mud buildings were destroyed directly by the impact of heavy rains (BBC, 2003). As the floodwaters moved downstream, record floods occurred along the mid- to lower reaches of other major rivers such as the Senegal, the Volta, and the Chari-Logone between September and November.

Accumulated rainfall in the three months from July to September at most observation stations in the drylands of West Africa exceeded long-term averages and record amounts from the past 50-70 years (up to 200-300% of the normal) (French, 2002/03a, 2003b). Some areas in the western parts of the southern to central Sahara had 500% or more of normal rainfall. Although there was widespread damage to human lives, houses, and other structures throughout the drylands of West Africa south of the Sahara, the wet conditions also supported the best cereal and cotton harvest in the Sahel in the past 50 years. Grain production for countries in the Sahel for 2003-04 was estimated as of March 2004 to be 32% above the mean total production for the last 5 years. In Senegal, grain production was 66 % above the 5-year mean. Per capita production also increased, 22 % above the mean for the last 5 years, which was a new record in the past 15 years (FEWS NET/CILSS, 2004).

2) Eastern Parts of the Sudano-Sahelian Region

Excessive and unusually heavy rains fell from late July to mid-August in eastern Sudan, northern Ethiopia, and Eritrea. In eastern Sudan, very heavy rains (500 mm) from 26-30 July caused widespread flooding east of Khartoum on the Blue Nile River and near Kassala on the Awash River (FEWS NET, 2003e). The flood event of the Awash River, which originates in the northern Ethiopia-Eritrea highlands, was the most severe in the last 70 years, flooding 79% of the houses and making 70,000 homeless in Kassala from mid-July to August. Localized record flooding and landslides occurred (DFO, 2003). Total numbers of those displaced from 28 July to 21 August 2003 reached 325,000 (DFO, 2003; Table 1).

3) Guinea Coast Region

Coastal regions along the Gulf of Guinea from Liberia to southern Nigeria are typically dry from July through early September because the ITCZ and its accompanying rainbelt usually move north into the Sahel during those months. In 2003, this dry season started about a month early across the coastal zone and also ended later. Thus, there were dryer conditions in the coastal zone during July-early September, reflecting the more northerly final position of the ITCZ compared to normal years (French, 2002/03a, 2003a) (Figs. 2, 3a). Drought conditions caused water shortages for rain-fed crops and resulted in the lowering of water levels in reservoirs, which led to a drop in hydroelectric power generation.

II. Equatorial East Africa and Southern Africa

1) Equatorial East Africa

June through August is generally dry over equatorial East Africa, including most of Kenya, Tanzania, and eastern Uganda, because the ITCZ is displaced north far from the Equator. However, in 2003, the western part of Kenya, which sits within the basin of Lake Victoria, experienced normal or above normal rainfall with frequent locally heavy rains (French, 2003/04b). Maximum total recorded rainfall during June-August was 861.9 mm at Kakamega in the Western Kenya Highlands. This three-month total, the greatest since 1958, was 161.3% of the long-term mean (Kenya Met. Dept., 2003). Between 26 August and 12 September, flooding occurred along the lower floodplains of the Nzoia and Yala Rivers. Dikes along the Nzoia River in the Budalangi Division of Siaya District collapsed for the second time that year leaving 2,500 homeless, most of whom also flooded the previous April (DFO, 2003; ReliefWeb, 2003d). Floodwaters of the Nzoia River originated mainly from downpours over head-waters in the Cherengany Hills and on Mt. Elgon (East African Standard, 2003).

2) Southern Africa

During winter 2003 in the Southern Hemisphere (June-September), most of the drylands, or regions that see summer rainfall in Southern Africa, experienced seasonal dryness. Parts of southern Mozambique, southern Zambia, eastern Botswana, and northeastern South Africa were in persistent hydrological drought conditions due to a long-lasted dryness since early 2003, particularly poor rainfall during the last rainy season (40-65% of normal) (FEWS NET, 2003b, 2003c, 2003d, 2000e; Fig. 3a). Unusually cold weather with temperatures 2-6°C below normal were common over much of southern Africa from June-August (French, 2003/04c).

In areas where winter rainfall is expected, particularly the Western Cape Province of South Africa, a dry July was followed by an abnormally wet August. The latter month was marked by the frequent passage of extratropical storms. On 18-20 August, a powerful storm over the South Atlantic Ocean swept a cold front into South Africa (Fig. 5). Heavy rains and floods, snows in higher elevations, and strong winds accompanied the storm. Winds over southeastern Cape Province exceeded 90 km/hr (with gusts to 130 km/hr), causing wind damage over parts of greater Cape Town. During the night of 20 August, record-cold August temperatures occurred across South Africa and Lesotho. Some stations reached -10°C, and black frost covered wide areas (South African

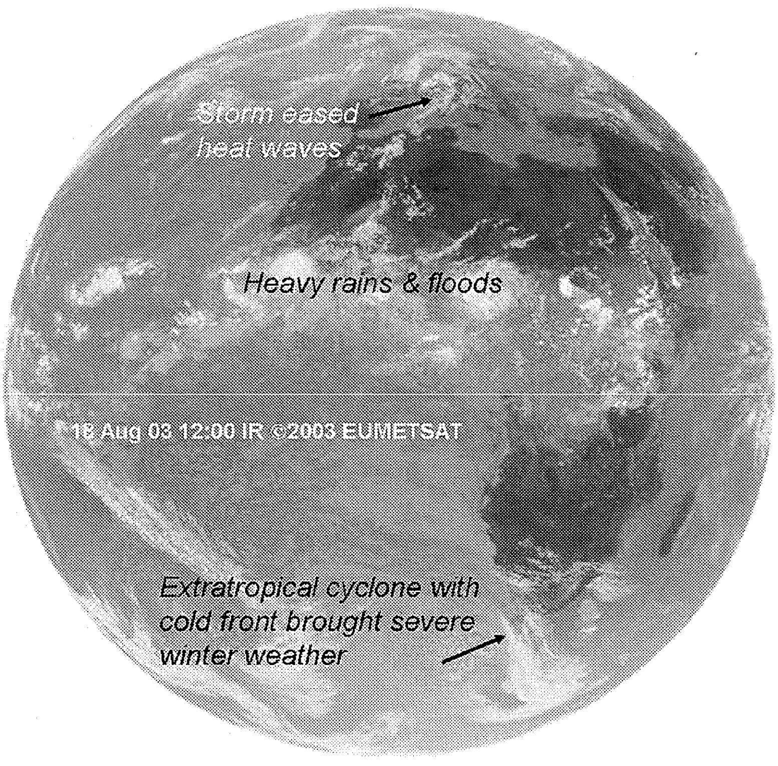

Fig. 5. METEOSAT infrared image on 18 August, 2003 at 12:00 UTC (Copyright ©2003 EUMETSAT; EUMETSAT, 2003b).
As Europe saw relief from persistent, record summer heat waves by the passage of a storm, southern parts of South Africa suffered under the influence of a strong extratropical cyclone accompanied by severe winter frontal weather (South African Weather Service, 2003a, 2003b). The Sahel region was at the height of the rainy season which was characterized by widely scattered heavy rains.

Weather Service, 2003a, 2003b).

CLIMATE ANOMALIES AND EXTREME EVENTS IN OTHER SEASONS OF 2003

A number of unusual events, such as heavy rains and floods, occurred in various parts of Africa, as shown in Fig. 3b and summarized below, during 2003 in months other than Northern Hemisphere summer (June-September):

I. January-March 2003

1. North Africa

Heavy rains associated with a temperate cyclone from 14-16 January caused flooding of ephemeral rivers in northern and central Tunisia, killing eight and displacing 27,000. Heavy rains continued in northern Tunisia until mid-January. Floods recurred there on 25-26 January, killing two people (DFO, 2003).

2. East Africa

Floodwaters on the Auji River that originated from heavy rains that fell in the Nandi Hills of western Kenya were clogged with water hyacinth (*Eichhornia crassipes*), one of the world's 100 worst invasive alien species. Flooding occurred over low-lying areas of the Kisumu estates along Lake Victoria from 4-6 January (DOF, 2003).

3. Congo Basin

A violent tornado struck six villages in the central Congo Basin in the District of Yumbi, Province of Bandundu, DR Congo (Fig. 3b), at 11 PM on 2 February. The tornado destroyed 1,664 houses, killed 164, and injured 1,702, and 1,970 families were made homeless (ReliefWeb, 2003b).

4. Southern Africa

Over Southern Africa, drought conditions prevailed during the Southern Hemisphere rainy season from December 2002-March 2003. Total rainfall across western Zimbabwe, extreme eastern Botswana, and northeastern South Africa was only 40 to 70% of normal (FEWS NET, 2003e; French, 2002/03b). During the same period, northeastern Southern Africa, including Madagascar, received normal to above normal rainfalls. Tropical cyclones, or the remnants of tropical cyclones, were frequent (Fig. 3b).

During January, extremely wet conditions prevailed over Madagascar. Monthly rainfall totaled 400 to 900 mm (170-360% of normal). Similarly, very wet weather was common across northern Mozambique, Malawi, and parts of eastern Zambia, where monthly totals were 300-400 mm, or 120-150% of normal (French, 2002/03b). Ex-Tropical Cyclone Delfina, which made landfall over northern Mozambique on 31 December 2002 (Fig. 6a), produced heavy

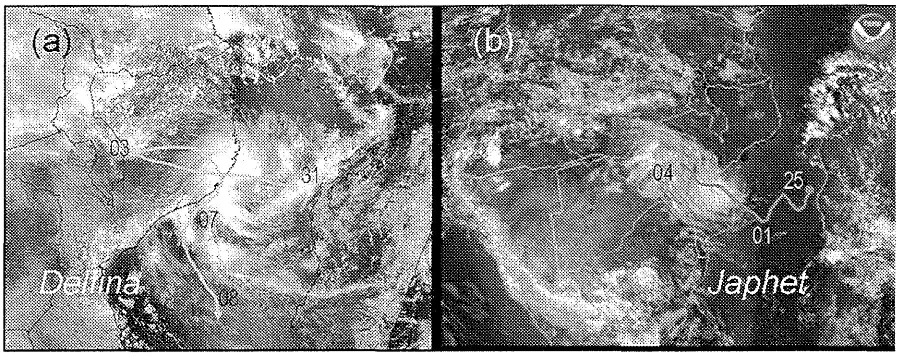

Fig. 6. Two tropical cyclones that made landfall on the east coast of Mozambique during January-March 2003 (Tracks from JAXA/EORC, 2003).

(a) Tropical Cyclone Delfina just before made landfall on the east coast of northern Mozambique with heavy rains over parts of northern Mozambique and Malawi (MODES image on 31 December, 2002 from NASA/EONH, 2002; Track from 31 December, 2002-4 January, 2003 from JAXA/EORC, 2003).

(b) Tropical Cyclone Japhet made landfall on the east coast of central Mozambique and heavy rains spread over central Mozambique and most of Zimbabwe (DMSP F-14 2.7 km visible imagery on 4 March, 2003 at 13:00 UTC from NOAA/EVP, 2003; Track from 25 February-4 March, 2003 from JAXA/EORC, 2003).

rains (up to 600% of normal) over northern Mozambique, parts of Malawi, and northern Madagascar (French, 2002/03c) on 4-5 January. Resultant floods damaged crops, roads, bridges, and urban water supply systems. Furthermore, 18,000 to 20,000 houses were destroyed, and 350 schools were damaged. The number of affected people was 100,000 as of 10 January (ReliefWeb, 2003a). Flooding continued from 1 January to 17 February, killing 23 people and displacing 400,000 (DFO, 2003).

Cyclone Fari made landfall on 28 January along the east-central coast of Madagascar, with 24-hour rainfalls of up to 230 mm on the west coast. From 18-31 January, 16 people died and 25,000 people were displaced because of flooding on the Ikopa River in and around Madagascar's capital Antananarivo (DFO, 2003).

During the first ten days of February, very heavy rains up to 339 mm fell over northeast Madagascar as Cyclone Gerry developed. A tropical disturbance in late February produced very heavy rains (170-344 mm) across west-central Madagascar. This disturbance developed into Tropical Cyclone Japhet on 26 February, bringing heavy rains over northern Zimbabwe, southern Zambia, and central Mozambique (French, 2002/03b; Fig. 6b). Between 4 and 8 March, remnants of Tropical Cyclone Japhet dropped very heavy rains (up to 373 mm /603% normal) (French, 2002/03b) across much of central Mozambique and eastern Zimbabwe. These rains caused flooding of the lower Limpopo, the Save, and other rivers in coastal Mozambique (SAFDN, 2003), killing eight and displacing 8,300 (DFO, 2003).

In the floodplains of the upper to middle reaches of the Zambezi River and its tributaries, including areas across Angola, southwestern Zambia, northeastern Namibia, and the Caprivi Strip, seasonal flooding began earlier and became more serious than usual in early April because of heavy rains over the headwaters on the Angola Highlands that had persisted since December 2002. Mongu, which is located in the Barotse Plain of western Zambia, experienced the worst floods in 50 years; twenty-five villages washed away (DFO, 2003). Flood waters around Mongu receded by mid-May, but floods continued downstream, especially in eastern Caprivi, through June and early July with 22 villages submerged or surrounded by water and 12,000 people displaced. This was the worst flood in about 20 years, and the Government of Namibia declared a flood crisis over Caprivi on 3 June. Floods in the Zambezi Basin during the 6 months starting 1 January killed seven and displaced 20,000 (DFO, 2003).

II. April-June 2003

1. East Africa

The year's first flood in western Kenya occurred in late April, forcing the evacuation of 18,000 (ReliefWeb, 2003c). In the last ten days of April, Kenya recorded abnormally heavy rains (77-260 mm, 126-624% of normal) across its inland areas (French, 2002/03b). Weekly rainfall during 29 April-5 May exceeded 150 mm in some areas. Heavy rains aggravated flooding through May over much of Kenya and eastern Uganda, where 77 died and one million were displaced between 21 April and 3 June (DFO, 2003). The areas most affected were the flood-prone lowlands of Nyanza and Western provinces, as well as some districts in the Eastern and Northeastern provinces. As of 16 May, more than 35 had died and about 60,000 were displaced in floods in Kenya (MOFA, 2003) that affected alluvial lowlands along the lower reaches of the Nyando and Nzoia Rivers in the Lake Victoria Basin. Rivers in the Rift Valley such as the Kerio River and the lower Tana River also flooded (DFO, 2003).

In southern Ethiopia and adjacent areas of Somalia, the worst flooding in memory killed 106 and displaced 111,000 between 6-20 May (DFO, 2003)

2. Southern Africa

In May, in the middle of the normal dry season, late-developing tropical cyclone Manou (Fig. 3b) in the Indian Ocean dropped heavy rains (up to 570 mm, or 258% of normal) over the east coast of Madagascar (French, 2002/03b). From June 21-30, unseasonably heavy showers (more than 1000% of normal) hit the cost of southern Mozambique; above-normal rains (more than 600% of normal) also fell in eastern Zimbabwe (French, 2002/03b).

III. October-December 2003

1. West and North Africa

Over the western Sudano-Sahelian region, rainy conditions (5-56 mm, 109-940 % normal) prevailed over western Mauritania, Senegal, and Gambia as late as the last ten days of October, a time of year that is normally dry (French, 2003/04a). Unusually heavy rains fell over desert areas of northern and western Mauritania, Western Sahara, western Algeria, and southern Morocco on 21-22

October. Flash floods resulted from rainfall (more than 50 mm on 21 October) over parts of the Morocco–Western Sahara–Algeria border area (FEWS NET, 2003f). A torrential storm dropped 100 mm rain in 12 hours on 19 November in the mountainous areas of Morocco, causing flash floods that killed 13 (DFO, 2003). On 12 December, the heaviest rains in 30 years, more than 60 mm, fell along the coast of Tunisia; causing valley flooding that killed seven people (DFO, 2003).

2. East Africa

Heavy rains caused rare flooding on 20-21 December in Kilimanjaro region of northern Tanzania, destroying 500 houses and displacing 2,000 people (DFO, 2003).

3. Congo Basin and Adjacent Regions

In the central DR Congo, severe thunderstorms struck the area around Bikoro, Equator Province (some 120 km from Mbandaka) on 9 October. A school was hit by lightning; 11 died and 73 were injured (ReliefWeb, 2003g). Heavy rains continued from late November through December over south-central Africa, from Gabon, Equatorial Guinea, and Angola in the west to the DR Congo and into Uganda in the east (FEWS NET, 2003g, 2003h).

4. Southern Africa

During mid-December, Tropical Cyclone Cela, which made landfall in northern Madagascar, brought heavy rains of up to 200-300 mm over west-central and northeastern Madagascar and northern Mozambique (FEWS NET, 2003h; French, 2003/04c).

SUMMARY AND CONCLUDING REMARKS

As described above, the climate of Africa in 2003 was exceptionally abnormal and eventful. During Northern Hemisphere summer, as record heat waves hit Europe, Africa experienced unusually heavy rains and floods in the west-central Sahara, across the Sudano-Sahelian region, and western Kenya. Simultaneously, drought conditions affected the Guinea Coast and southeastern Southern Africa, and severe cold waves hit southern South Africa (Fig. 3). Of these events, the two most remarkable events were the extreme northward penetration of the ITCZ into the Sahara that caused record summer rainfall over the western portion of the Sahara-Sahel and drought conditions over the Guinea Coast and record-breaking cold winter weather over southern South Africa in mid-August (Figs. 2, 3a, 4, 5). All these events suggest a temporally overall northward shift of the climate system across Europe-Africa. During Southern Hemisphere summer, heavy rains and floods that accompanied tropical cyclones and their remnants frequently affected Madagascar, parts of Mozambique, Zimbabwe, and Malawi (Figs. 3b, 6). Lowlands in the Lake Victoria Basin of western Kenya repeatedly suffered from severe floods (Figs. 3a, 3b). In the seasonal floodplains of the Zambezi River and its tributaries, over-the-bank flooding set in earlier and ended later than in normal years. The flood victims throughout Africa in 2003, which are listed in the *Global Register of Major Flood Events 2003* (DFO, 2003), number in more than 550 died and more than 2.5 million displaced.

Many African countries are ill equipped to cope with flood hazards and therefore are highly susceptible to flood damage to croplands, settlements, roads, water supply systems and other infrastructures, and subsequent acute food shortages (Suda, 2000; IPCC, 2001b). To reduce Africa's vulnerability to climate hazards, particularly flood hazards, greater enhancement of both short- and long-term coping strategies, at all levels, including sub-regional, national, and local levels, is required. These enhancements include monitoring flood hazards, early warning systems, flood control infrastructures, and other disaster preparedness measures, in addition to existing drought preparedness and management systems. Enhancements should be extended to indirect effects of heavy rains and floods such as plagues of desert locusts (FAO, 2004) and outbreaks of water-born ailments including malaria, rift valley fever, mumps, and eye infections.

Many of the climate anomalies and extreme events that occurred throughout Africa in 2003 may be manifestations of a regional response over Africa to anthropogenic global warming. In view of this, mechanisms and processes driving climate variations in current Africa must be explored in the context of global change. Special attention should be paid to coupled zonal and meridional atmospheric circulation variations and to the effects of sea surface temperature anomalies both in the Indian Ocean (*e.g.*, Shinoda & Kawamura, 1994; Saji *et al.*, 1999) and the Atlantic Ocean (*e.g.*, Vizy & Cook, 2001; Grannini *et al*, 2003). Interannual and interdecadal variations in the appearance of anomalies and events also warrant careful inspection and analysis.

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A VEGETATION-MAINTAINING SYSTEM AS A LIVELIHOOD STRATEGY AMONG THE SEREER, WEST-CENTRAL SENEGAL

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ABSTRACT A field study of the system of maintaining vegetation practiced by the Sereer people was conducted from October 2001 to July 2002 at N village, located in the Thiès Department of west-central Senegal. For centuries, the Sereer people have practiced millet cultivation in combination with livestock raising and have maintained a unique form of artificial vegetation, dominated by the tree *Acacia albida*. The aim of this study was to reveal how the Sereer use and maintain the vegetation. *Acacia albida* contributes to their livelihood in several ways by functioning, for example, as a green manure and as fodder for livestock. The Sereer deliberately maintain the vegetation through "*yar*", which means to grow *Acacia albida* seedlings in cultivated fields. A "*yar*" behavior is one associated with "upbringing" in the Sereer idiom. Use of this tree up to the 1970s helped to make the Sereer livelihood system more secure in an erratic, semi-arid climate.

Key Words: Senegal; Sereer; *Acacia albida*; livelihood activities; vegetation-maintaining system.

INTRODUCTION

A unique, artificial vegetation type, described as farmed parkland, is found over a broad section of West Africa, from the Sahel-Sudan to the Guinea zone. In this type of vegetation, tall trees (of different species, in different regions) are intercropped and scattered in cultivated fields. This farmed parkland has been created by local people, and is associated with their livelihood activities (Pullan, 1974).

As a typical example, the Sereer people living in west-central Senegal, located in the Sahel-Sudan zone, have for centuries been creating and maintaining a farmed parkland that is clearly different from the natural vegetation, and is dominated by *Acacia albida* (henceforth "albida vegetation"). *Acacia albida* (synonym: *Faidherbia albida*), a tall leguminous tree, has a unique characteristic described as reverse phenology, which means that the tree sprouts leaves in the dry season and sheds its leaves in the rainy season (Roupsard, 1999); this characteristic uniquely suits the tree to contributing to livelihood activities such as millet cultivation and cattle raising. The Sereer have been maintaining albida vegetation for centuries because it helps to make their livelihood more stable and secure under erratic climate conditions, including a long dry season and low and erratic rainfall, and high population density.

In this paper, we explain how the Sereer created and maintained albida vegetation before the 1970s, with reference to the relationship between *Acacia* *albida* and the livelihood activities of the Sereer. Many studies on *Acacia albida* have been conducted since the 1960s, but most of these have been agricultural or biological studies on the availability of the tree for agroforestry or development (Louppe, 1996; Depommier *et al.*, 1992; Kho *et al.*, 2001). Studies of how the local population recognize, use, and maintain the albida vegetation have not been made. Although it has recently been noted that farmers, such as the Sereer, in some areas of the Sahel-Sudan are no longer protecting the natural regeneration of albida vegetation, and the use of the tree is declining in spite of its potential (Seyler, 1993: 4), the reason for this is not clear. Seyler found that albida vegetation use by the Sereer has declined since the 1970s, with a change in the people's behavior toward *Acacia albida* resulting from changes in their livelihood system. It is important to understand the vegetation-maintaining system that was formerly in place in order to understand why this transformation is taking place.

STUDY SITE AND METHOD

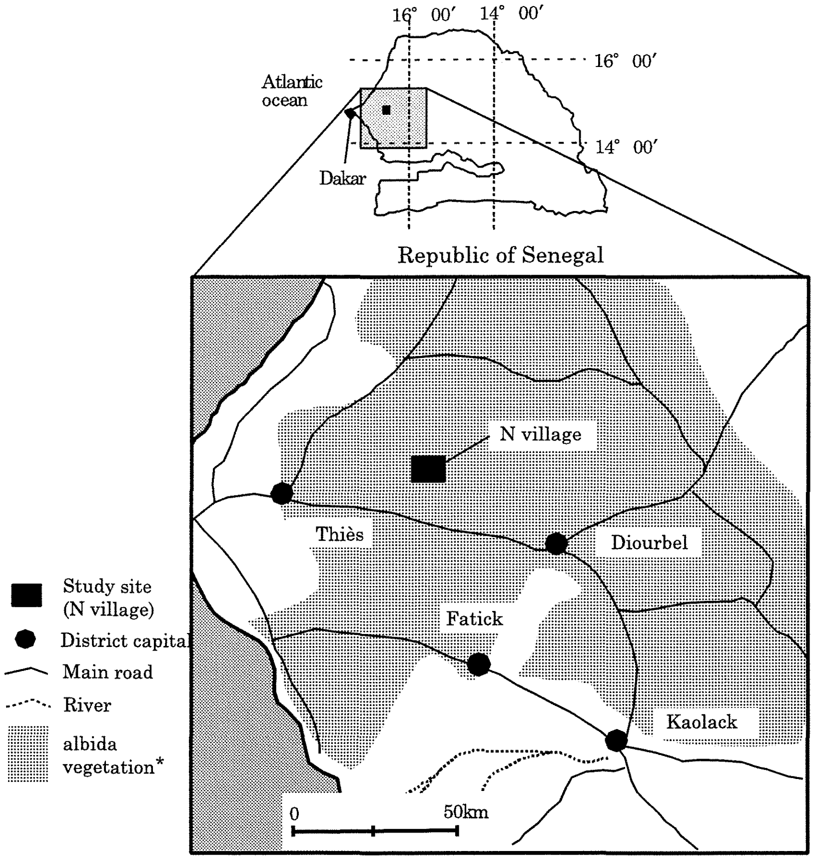
I. Study Site

The field research was conducted from October 2001 to July 2002 at N village, located in the Thiès Department of west-central Sénégal (Fig. 1).

Precipitation levels vary greatly across Senegal, from 50 to 1500 mm per year, and the flora changes in connection with the precipitation levels, but *Acacia albida* occurs over almost all of the country owing to its ability to adapt to a wide range of climate conditions: annual rainfall from 200 mm to more than 1500 mm, and temperatures from 4 to 40°C (Wood, 1992). However, the region where this tree occurs acervately is restricted to an area within west-central Senegal where the local people (Sereer) have been practicing millet cultivation and cattle raising for a long time (Fig. 1) (Pélissier, 1980). Gastellu (1981) noted that *Acacia albida* acervating in cultivated fields was one of the common features of the landscape where the Sereer lived.

N village is in the Sahel-Sudan zone, which has a mean annual rainfall of about 400–600 mm and a dry season that lasts about eight months. The potential natural vegetation is mainly acacia woodland, dominated by leguminous tall trees and germanous grass.

The Sereer people have a sedentary lifestyle and seldom move their residences. The people of N village have been living in one place for 200–300 years, or for about 11 generations. The population was 970 in 2001, with a population density of more than 200 individuals/km^2. Almost 90% of the population belong to the same clan. Their major livelihood activities are agriculture and livestock keeping. They grow bulrush millet as a subsistence crop and groundnuts as a cash crop. The keeping of cattle was common before the 1970s.



* referred to *Atlas du Senegal* (Pélissier, 1980: 19)

Fig. 1. Location of the study site and extent of the albida vegetation.

II. Method

To understand the formation and maintenance system of albida vegetation, we need to know how *Acacia albida* contributes to the livelihood activities of the Sereer. First, I recorded general points pertaining to livelihood activities that took place before the 1970s, such as types of land use, the agricultural calendar, and cattle-keeping methods, by conducting interviews and a land survey, and discussed the utilization and recognition of *Acacia albida.*

Second, I carried out a tree census, employing the line-transect method, to describe the albida vegetation from an ecological point of view. Twenty-four plots along nine transects, with a total surface area of about 9 ha, were set across the fields of N village, and all trees with a diameter at breast height (DBH) of more than 1 cm were measured for DBH and height; the frequency and basal area of each species were calculated based on these data. Likewise, vegetation located near N village, under the same climate and soil conditions but subjected to less human influence, was also measured in order to determine differences between albida vegetation and natural vegetation in terms of tree species composition and size.

I also observed the behavior of the people toward *Acacia albida.* This behavior is called *yar* in Sereer. Because the people practice this type of behavior when they intend to keep seedlings of *Acacia albida* in their fields (Pélissier, 1966), *yar* could be a key word in describing their vegetation-maintaining system. For this reason, I have developed a description of this behavior and an analysis of the ecological, social, and cultural conditions associated with it.

UTILIZATION OF *ACACIA ALBIDA*

The land-use system clearly differs, depending on whether it is operational in the dry season or the rainy season (Fig. 2). Before the 1970s, in the rainy season, after shifting the cattle kraal to outside the field, the people employed 70% of the field to cultivate bulrush millet and groundnuts; the remaining land was left fallow for cattle grazing. In the dry season, the cattle kraal was established in the fields after crops had been harvested, and the residue of crop and leaves of *Acacia albida* were given to the cattle as forage. The distinctive feature of such a land-use system is that the field was employed throughout the year — for agriculture in the rainy season and grazing in the dry season (Pélissier, 1966; Lericollais, 1999).

This annual cycle of land use is related to the peculiar reverse phenology of *Acacia albida*. In the rainy season, the time of cultivation, usually from June to October, the trees shed their leaves and the nitrogen-rich leaves fertilize the millet growing around the tree. Moreover, owing to the absence of leaves, more sunlight reaches the crop (Louppe, 1996).

The trees sprout leaves again at the end of the rainy season and produce seed pods in the middle of the dry season. The seed pods are rich in protein and are good forage for livestock. Thus, the *Acacia albida* tree contributes to the Sereer livelihood in both the rainy season and the dry season.

The people explain the combination of trees with bulrush millet as follows: "Seven adult trees can fill up a granary with bulrush millet," or "Bulrush millet can grow much better, even around a dead tree for several years, than at a place with no tree". In fact, Loupe (1996) reported that bulrush millet, influenced by

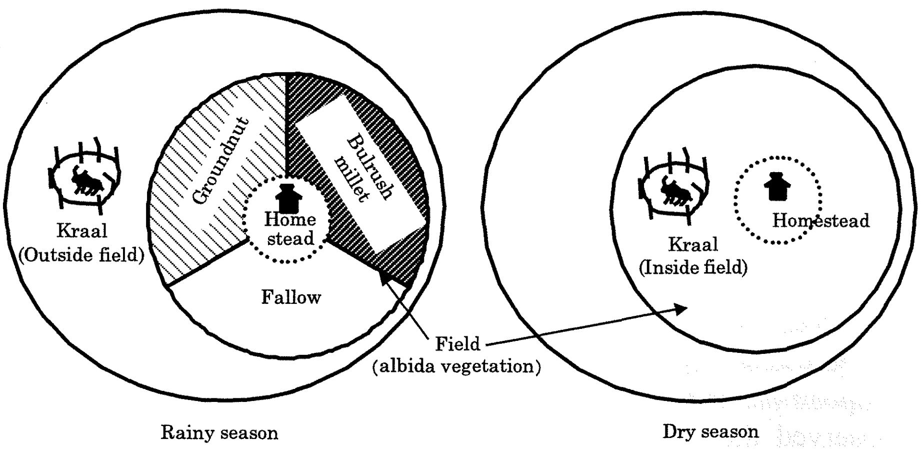


Fig. 2. Annual cycle of land use before the 1970s.

trees, can produce an increased yield (measured as the dry weight of the millet seeds) of as much as 150%. The Sereer also describe the contribution of the tree to cattle rearing in this way: "It has been possible to keep cattle by giving them only the pods of the tree in the dry season". Thus, the tree is thoroughly utilized in the long dry season.

Millet, cattle, and *Acacia albida* are thus synergistic in the cultivated fields of the Sereer. In addition to the contribution of *Acacia albida*, as described above, to the yield of millet and as cattle fodder, the cattle dung provides fertilizer for cultivated fields and the cattle can eat the stalks and leaves of millet in the fields after harvesting.

ECOLOGICAL FEATURES OF ALBIDA VEGETATION

A tree census of albida vegetation was conducted at N village to describe the species composition and size structure of the forest. At N village, 13 tree species, including *Adansonia digitata* (baobab), *Balanites aegyptiaca,* and *Acacia nilotica*, were observed with a population density of 31.1 stems/ha. The most common species was *Acacia albida*, accounting for 83% of all trees (Table 1). *Acacia albida* also represented 70% of the total basal area. The mean DBH of *Acacia albida* was 42.6 cm (N=220, minimum=22.7 cm, maximum=88.0 cm), and all of the trees in the population were adults.

In the area of vegetation outside the village, which were less influenced by human activities, overall tree density was 43.9 stems/ha and 14 species were represented (Table 1). The frequency and size of *Acacia albida* were much lower than in the albida vegetation. In addition, although the vegetation in the area less influenced by human activities had species richness, the biomass was much less than in the albida vegetation dominated by *Acacia albida*. This difference could have been caused by the intervention of the Sereer.

VEGETATION-MAINTAINING SYSTEM

I. "Upbringing"

How have the Sereer been creating and maintaining this albida vegetution for centuries? To answer this question, I observed the behavior of the people toward *Acacia albida*, or "*yar*" in the Sereer idiom, a word meaning "upbringing." By way of example, disciplinary behavior on the part of parents towards their children, such as striking them when the children did something wrong, is termed *yar*. When applied to *Acacia albida* culture, the word means "to grow the tree."

The people practice "upbringing" toward both of seedling (*njaas* in sereer) and adult tree (*saas*). First, about seedling, they start to treat it after seedlings grew in certain size (0.5 to 1 m) in cultivated field. Normally the branches of

Table 1. Frequency and Rate of Basal Area of Each Species (DBH≧1 cm) in albida vegetation and vegetation less influenced by human

Species	albida vegetation			vegetation less influenced by human		
	Frequency (%)	Mean DBH (cm)	Rate of basal area (%)	Frequency (%)	Mean DBH (cm)	Rate of basal area (%)
Acacia albida	82.95	42.60	69.93	21.05	35.08	43.88
Acacia nilotica	1.89	44.31 (4.19)	0.98	1.75	st	
Acacia sieberiana	0.38	2.5 (–)	0.01			
Acacia tortolis	0.38	22.54 (–)	0.08	1.75	15.5 (–)	0.68
Adansonia digitata	7.95	46.73	14.19	1.75	st	
Anogeissus leiocarpus	0.38	106.91 (–)	1.88			
Azadirachta indica				1.75	13.9 (–)	0.68
Balanites aegyptiaca	2.27	13.23	0.53	24.56	20.71	19.73
Bauhinia rufescens	0.38	23.76 (–)	0.09	1.75	7.9 (–)	0.34
Borassus flabelifer	0.38	49.11 (–)	0.4			
Cassia sieberiana				1.75	26.5 (–)	2.04
Celtis integrifolia	1.52	108.5	11.2			
Combretum glutinosum				7.02	9.47 (5.99)	1.36
Parinari macrophylla				1.75	st	
Piliostigma sp.	0.38	2.27(1.5)	0.01			
Prosopis africana				29.82	24.24	27.21
Securidaca longepedunculata				1.75	9.5 (–)	0.34
Tamarindus indica	0.38	51.56 (–)	0.44	1.75	37.6 (–)	3.74
Zizphus mauritiana	0.76	27.36	0.27	1.75	st	
Total number of trees (ha^{-1})	31.1			43.85		
Total basal area (m^2ha^{-1})			5.53			2.94

* Standard deviation is given in parentheses. (–) indicates species having only one stem in the plot.

** st: Stool sprouting after cutting by local people from bottom were observed in the vegetation less influence. Among these trees, if the DBH was estimated to be more than 1cm under the normal condition, I counted it to calculate frequency.

the seedlings would spread toward wise and be disruptive to the cultivation of millet, because they are coppiced: the seedlings are so small before "upbringing" and are unconsciously cut down when the people cultivated their fields. The Sereer people interviewed for this study said, "The seedling that spread the branches itself cannot grow upwards". So the people trim the spreading branches and retain the main stem, encouraging a more vertical growth form of the tree. Regarding the adult trees, although the people cut down branches for firewood or fodder, they cut branches very carefully, giving consideration to later growth. For example, they may first cut only branches on the left, and then after two years they may switch to cutting branches on the right. If they trim the branches well they say that the acute thorns of the tree will be flat and this type of tree are called "sweet trees". The young branches of these "sweet trees" can be used easily as fodder for their livestock.

It is important to note that, in the case of seedlings, the Sereer practices of "upbringing", to accelerate the growth of the tree by means of improving the tree form are designed to make the *Acacia albida* compatible with their cultivated fields. With respect to the adult trees, they focus on transforming "sweet trees" by cutting branches that provide fodder for livestock. Thus, we can

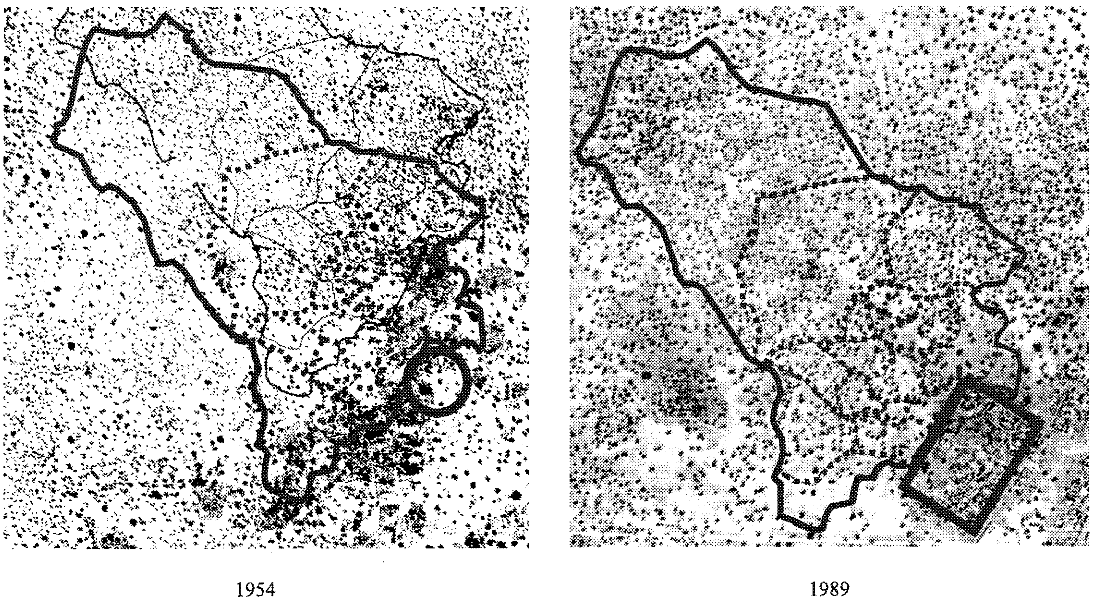


Fig. 3. Aerial photographs showing N village, 1954 (left) and 1989 (right).
Solid and dotted lines indicate the boundary of N village and the division of fields held by different households. Circles and squares indicate homesteads. Source: A079/400.334 (left), Institut Geographique National, Paris, France, and CT SGN L21A8 (Light), Direction Geographique, Dakar, Senegal.

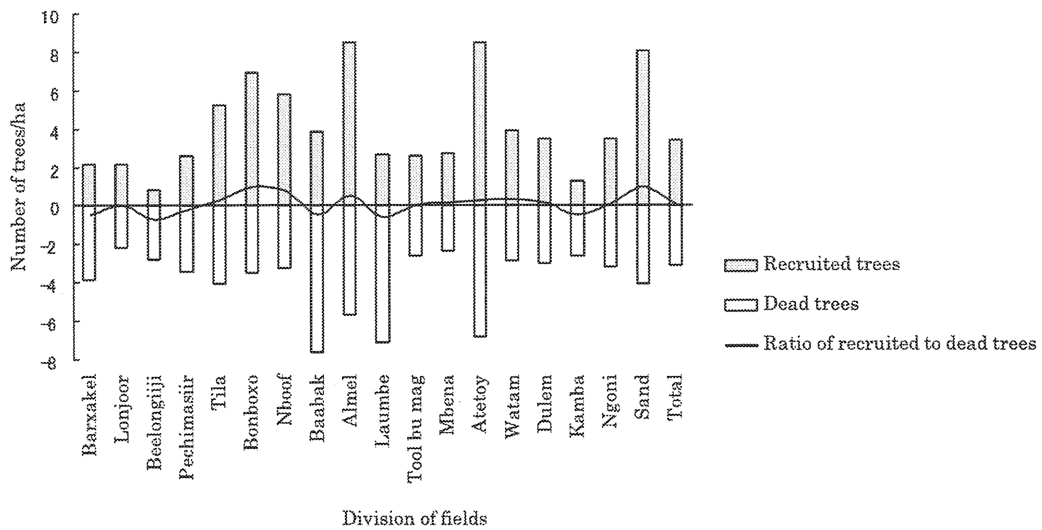


Fig. 4. Recruited and dead trees in N village between 1954 and 1989.
Letters under the horizontal axis refer to the names of each division of the fields. The total numbers of recruited and dead trees during this period were estimated at 309 and 279. The ratio of recruited to dead trees was calculated as 1 − (number of recruited trees ÷ dead trees).

define Sereer "upbringing" as a deliberate manipulation of the vegetation through the improvement of growth and the preservation of individual trees.

By comparing aerial photographs taken in 1954 and 1989 (Fig. 3), we can see how the people have maintained the albida vegetation through "upbringing". Two photographs showing the same individual trees in 1954 and 1989 were compared, and the numbers of dead and recruited individuals were counted. A dead individual was defined as a tree present in 1954 but not present in 1989. A recruited individual was defined as a tree that was not present in 1954 but was present in 1989. All trees counted were visible adults in one of the photographs, and at least 20 years old. The dead and recruited individuals over these 35 years were examined from 18 cultivated fields of the village (Fig. 4). The total number and density of the trees had not changed from 1954 to 1989, in all the cultivated fields, held by different landowners. The number of *Acacia albida* had been kept in dynamic equilibrium through "upbringing", practiced by the people in their fields.

II. Conditions for the Practice of "upbringing"

Even though the Sereer practices associated with "upbringing" do not seem to be difficult, several social and ecological conditions must be met in order for treated trees to grow and become adults in the livelihood system. A seedling needs more than 20 years to become an adult, and many difficulties may be encountered during this period that could interfere with the treatment.

First, dispersion and germination of the seed in cultivated fields is a precondition for the practice of "upbringing." Livestock disperse the seed and accelerate germination by eating seed pods (Halevy, 1974; Hauser, 1994). After germination, the seedling must grow until it becomes large enough for recognition, in order that it may be treated. For establishment of the seedling, a fallow field stage, such as that practiced before the 1970s, is also required. In addition, cutting the millet with a hoe rather than with a machine is important to avoid cutting down the seedlings.

It takes more than 20 years to gain the benefits from the treated seedling, therefore a system of inheritance with respect to the cultivated fields is an important factor in perpetuating continual "upbringing." The *Acacia albida* in a villager's fields have been treated by his great-grandfather, grandfather, and father (Fig. 5). Thus the people have been able to practice "upbringing" with a long perspective in mind, because the cultivated fields are inherited through the patrilineal line by descendants. A stable land inheritance system, then, is an important social precondition for "upbringing."

The cultural value attached to the trees as Gravrand mentioned (Gravrand, 1973; 1990) is another important factor, along with the ecological and social preconditions for "upbringing". For example, parents teach their children that "if you cut down a seedling, you will die or you will never grow to be big." There are even some sacred *Acacia albida*, known as *Saas Djieu*, in the cultivated fields. The people pray to them for good harvests and leave offerings

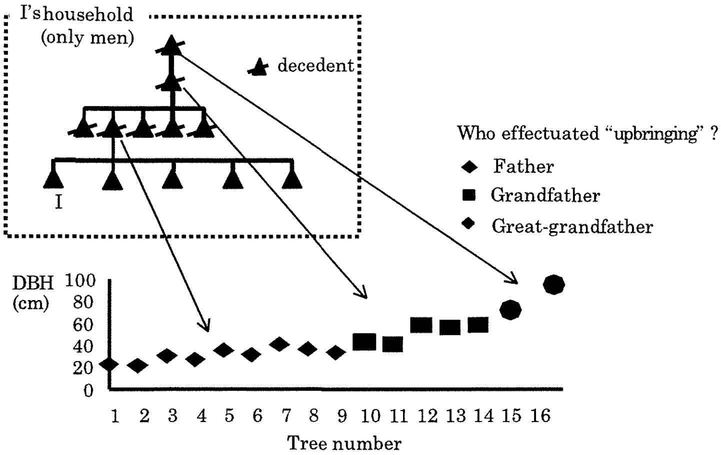


Fig. 5. Who carried out "upbringing" in the case of I's household?
I is in his fifties. He inherited the fields from his father and farms them with his brothers.

of camel bone or millet seeds at the trees.

CONCLUSION

Before the 1970s, the Sereer people maintained *Acacia albida* through the practice of "upbringing" in order to enhance the stability of their livelihood system. To perpetuate "upbringing," it was necessary that certain ecological, social, and cultural preconditions be met in relation to the Sereer society. It is possible, too, that the vegetation-maintaining system itself evolved in just such a social frame.

However, this vegetation-maintaining system seems to have transformed since 1970s. In evidence, the result of size class distribution of *Acacia albida*, based on tree census conducted in N village shows that this albida vegetation almost never has seedling or young tree of *Acacia albida*. It means that actually this vegetation is in lack of recruited trees or in no regeneration. It implies that the people has not been practicing "upbringing" for recent 20 to 30 years, considering growth rate of *Acacia albida* that would take 20 to 30 years to be 20 cm in thickness. Why they did not "upbringing" for this duration?

As it was already pointed out, the people practiced "upbringing" by reason of having good yield of millet and fodder for cattle. Only quarter of households could manage to secure millet sufficiently by their yield in 2001. The other households bought imported rice to supplement the shortage. Although the rice was seldom eaten before 1970s, it became an important lunch recipe recently. This change is related to an increase of population and frequent drought spells. The fluctuation of annual rainfalls since 1950 is quite big. Although to cultivate millet needs an average of 400 mm per year, the rainfall achieved less than 400 mm in many years especially since 1970s. The number of cattle held by each household has been also changing. The cattle number decreased so highly since 1960s or 1970s. It would be in relation to drought and disappearance of fallow stage for feeding as well.

While the decrease of self-sufficiency rate, migration of labor in cities increases. If we see the rate of the male population being 15 to 70 years old who work in several cities and not return to the village throughout the year, it is clear that more than 40% of men have migrated. And also this causes shortage of agricultural labor and spread of horse plow for cultivation. The spread of the cultivation plow was deeply in relation to "upbringing". Although this people who cultivated by using plow detoured avoiding the seedling, generally larger part of the seedlings are cut down. Also, because the thorn of seedling injures foots of horse, the seedling become on an awkward existence.

The social conditions of "upbringing" also changes. The households belonging to the same patrilineage cultivated in form of joint labor beyond the consumption unit before diffusion of plow in 1970s. However, this labor organization has fragmented and they cultivate in individual consumption unit. Such a change is associated with shortage of labor caused by increase of migration, purchase of plow or horse with the money gained by migration work as well. The migration would influence to not only spread of the plow cultivation but also to the land tenure system. It is to say that they begun borrowing and lending of their land with diffusion of the land fragmentation. The borrowing and lending is practiced by 50% of the total household in the village. Thus, with the advance of the land mobilization, it is supposed that the people could not effectuate "upbringing" in the long view like before 1970s.

Since 1970s the Sereer people hardly practice "upbringing". As its background, first, I suggest the decline of relative importance of *Acacia albida*, caused by a decrease in dependency on the millet cultivation and holding cattle in their livelihood and generalization of migration labor. And second, as a result of such livelihood changes, the precondition for "upbringing" has also been transformed, and to practice "upbringing" is becoming more and more difficult. Actually, albida vegetation faces lacks of sustenance in the situation of no "upbringing". As changes in the people's livelihood strategy have been taking place, albida vegetation has also been transforming.

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VEGETATION SUCCESSION IN RELATION TO GLACIAL FLUCTUATION IN THE HIGH MOUNTAINS OF AFRICA

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ABSTRACT Dramatic changes are taking place in the glacier-covered high mountains of Africa. The glacier-covered area on Kilimanjaro is now only half as large as it was in the 1970s. The Tyndall Glacier on Mt. Kenya, which retreated at approx. 3 m yr^{-1} from 1958 to 1997, retreated at ca. 10 m yr^{-1} from 1997 to 2002. Pioneer species such as *Senecio keniophytum*, *Arabis alpina*, mosses, lichen, and *Agrostis trachyphylla* have advanced over areas formerly covered by the glacier. The rate at which this vegetation migrated up the former bed of the glacier (2.1–4.6 m yr^{-1} from 1958 to 1997) is similar to the rate of glacial retreat (2.9 m yr^{-1}). In the interval from 1997 to 2002, pioneer species advanced at a rapid rate of 6.4 –12.2 m yr^{-1} when the glacier retreated at 9.8 m yr^{-1}. Rapid glacial retreat has been accompanied by rapid colonization by plants. Pioneer species improve soil conditions and make habitat suitable for other plants. If warming continues, alpine plant cover may extend all the way to mountain summits, and then eventually diminish as trees colonize the areas formerly occupied by the alpine plants. Larger woody plants such as *Senecio keniodendron* and *Lobelia telekii*, which showed no obvious advances before 1997, have advanced quickly since 1997.

Key Words: Vegetation; Deglaciation, Global warming; Environmental change; Alpine zone; Africa

INTRODUCTION

Vegetation at glacier fronts is commonly affected by glacial fluctuations (Coe, 1967; Spence, 1989; Mizuno, 1998). Coe (1967) described vegetation zonation, plant colonization, and the distribution of individual plant species on the slopes below the Tyndall and Lewis Glaciers. Spence (1989) analyzed the advance of plant communities in response to the retreat of the Tyndall and Lewis Glaciers for the period 1958 to 1984. Mizuno (1998) addressed plant communities' responses to more recent glacial retreat by conducting field research in 1992, 1994, 1996, and 1997. These studies illustrated the link between ice-retreat and plant colonization near the Tyndall Glacier and Lewis Glacier. In addition, till age and substrate stability are critical controls on vegetation patterns around the glacier (Mizuno, 1998).

Numerous studies have been carried out on the glaciers of Mt. Kenya (Gregory, 1894, 1900; Mackinder, 1900; Troll & Wien, 1949; Charnley, 1959; Coe, 1964; Kruss & Hastenrath, 1983; Hastenrath, 1983, 1984). Many of these studies dealt with glacial fluctuations and deposits (Baker, 1967; Mahaney, 1979, 1982, 1984, 1989, 1990). Recently, mountain glaciers in Africa have been retreating at an accelerated rate (Hastenrath, 1997; Thompson *et al.*, 2002). This study focuses on glacial fluctuations over the period 1997 to 2002; it clarifies the response of plant communities to recent glacier retreat, and discusses the effects of glacial retreat on ecosystems. The habitats of large woody plants such as *Senecio keniodendron* and *Lobelia telekii*, which are characteristic plants of tropical high mountains, are examined.

STUDY AREAS AND METHODS

I. Study Area

Mt. Kenya is an isolated, extinct, denuded volcano that lies on the equator (0°6'S, 37°18'E), approx. 150 km NNE of Nairobi. The summit, Batian, is 5,199 m above sea level (Fig. 1). The mountain was built up by intermittent volcanic eruptions between 3.1 and 2.6 million years ago (Bhatt 1991), and the volcanic plug was dated to 2.64 million years ago (Everden & Curtis, 1965; Mahaney, 1990). Rocks of the volcanic massif consist of basalt, phonolite, kenytes, agglomerates, trachyte, and syenite (Baker, 1967; Baker *et al.*, 1972; Bhatt, 1991; Mahaney, 1990).

The Tyndall Glacier is the second largest glacier on Mt. Kenya, after the Lewis Glacier. Fluctuations of these glaciers have been recorded in detail (Gregory, 1894, 1896, 1900, 1921; Mackinder, 1900, 1901; McGregor Ross, 1911; Dutton, 1929; Light, 1941; Howard, 1955; Hastenrath, 1984; Mahaney, 1990). Mahaney (1984, 1990) subdivided Neoglacial deposits into two advances (Tyndall advance and Lewis advance) on the basis of several relative dating (RD) criteria, including topographic position, weathering characteristics, and degree of soil profile expression.

The Lewis and Tyndall Moraines formed in front of the Tyndall Glacier (Fig. 1). The Lewis Till (the Lewis Moraine, ca. 100 yr BP) and Tyndall Till (the Tyndall Moraine, ca. 900 yr BP) are considered to be late Holocene in age,

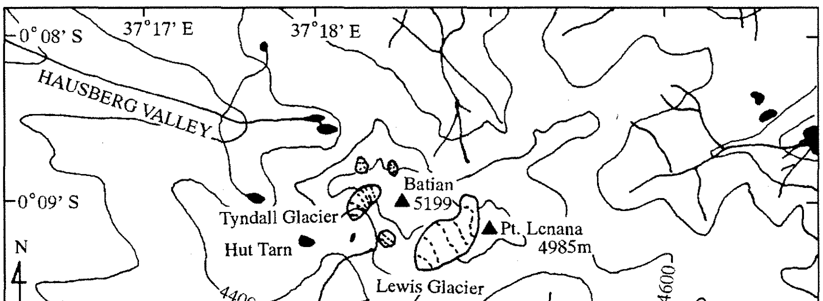

Fig. 1. Alpine zone of Mount Kenya.

based on soil development and weathering features (Spence & Mahaney, 1988; Mahaney, 1989, 1990; Mizuno, 1998). The Tyndall Moraine is divided into Tyndall Moraine I and Tyndall Moraine II on the basis of topographic position, weathering characteristics, and relative soil development (Mizuno, 1998, 2003a).

The elevations at which the annual minimum, mean, and maximum temperatures of the free atmosphere in East Africa are 0°C, are approx. 3,500 m, 4,750 m, and 6,000 m, respectively (Hastenrath, 1991). The precipitation is southeasterly maximum resulting from the classical monsoon, and secondary maximum on the western side (Mahaney, 1990). Annual precipitation is about 2,500 mm per year at 2,250 m on the southeast slopes of Mt. Kenya, grading to less than 1,000 mm per year at same altitude on the north slope (Hastenrath, 1991; Mahaney, 1984). Annual rainfall is highest between 2,500 and 3,000 m on the south, west, and east slopes, and decreases towards the peak (<900 mm at 4,500 m–4,800 m). Above 4,500 m, most of the precipitation falls in the form of snow and hail.

Vegetation on Mt. Kenya has been classified into the Alpine Belt (>3,600 m), the Ericaceous Belt (3,600 m to 3,400 m on the south slope, 2,900 m on the north slope), and the Montane Forest Belt (<3,400 m; Hastenrath, 1984). The vertical distribution of *Senecio keniodendron* and *Senecio brassica* is used to distinguish the upper and lower alpine zones, although there is considerable overlap in their distribution (Hedberg, 1951). In the lower alpine zone, tussock grasses, *Senecio brassica*, and *Lobelia keniensis* occupy the wetter areas, and *Alchemilletum* predominates in dry areas. In the upper alpine zone, *Senecio keniodendron* is present up to 4,500 m, together with *Carex monostachya*, *Agrostis* spp., *Cardus platyphyllus*, *Arabis alpina*, *Senecio keniophytum*, and *Lobelia telekii*.

II. Methods

The position of Tyndall Glacier's snout was established by measuring the distance from a sign at Tyndall Tarn. The leading edge of plant-cover was measured from the terminus of the glacier. Moraine positions were compiled on a topographic map (The Glaciers of Mount Kenya, 1:5,000, Hastenrath *et al.*, 1989) from field surveys and aerial photographs (1:50,000).

Plant communities and their environments were surveyed at nine sites (Plots 1 to 9, each 2 m×2 m and representing different terrain conditions). In each survey site, surface materials, land surface stability, lichen coverage on exposed rock, vegetation coverage, and species composition were investigated. The particle-sizes in the surface rubble layer were measured by the long-axis of rubble (30 to 100 measurements at each quadrat). Substrate stability was established using the deflection of a painted line. Lichen cover was used as a cross-check for identifying stability, and to estimate the elapsed time from glacier release. Lichen coverage is the percentage that lichen covers the exposed part of the debris. Soil profiles were surveyed at 12 sites (Plots a to l). A till age for each plot was estimated using its distance from the glacier front and established glacial retreat rates [2.9 m yr^{-1} (1958–1992); 3.8 m yr^{-1} (–1958); Charnley, 1959]).

Habitats of large woody plants such as *Senecio keniodendron* and *Lobelia telekii* were investigated around Plot 6. The relationship between the clast size of surficial material and the height of *Senecio keniodendron* and *Lobelia telekii* was studied at two sites (15 m×15 m): Plot A (4,390 m, on Tyndall Moraine I) and Plot B (4,390 m, on a debris flow and outwash slope).

RESULTS

I. Fluctuation of the Tyndall Glacier and Glacial Topography on Mt. Kenya

The Lewis and Tyndall Moraines formed in front of the Tyndall Glacier (Figs. 2 & 3). The Lewis Till (the Lewis Moraine, ca. 100 yr BP) and Tyndall Till (the Tyndall Moraine, ca. 900 yr BP) are considered to be late Holocene in age, based on soil development and weathering features (Spence & Mahaney, 1988; Mahaney, 1989; Mizuno 1998). The date of Tyndall Moraine corresponds to that of the leopard discovered from the snout of the Tyndall Glacier in 1997 (Fig. 4) (Mizuno, 2005; Mizuno & Nakamura, 1999). The Tyndall Moraine is divided into Tyndall Moraine I and Tyndall Moraine II on the basis of topographic position, weathering characteristics, and relative soil development. The climate fluctuated between warm and cold periods prior to 100 yr BP, and was accompanied by moraine deposition. In the last 100 yr, however, the Tyndall Glacier has retreated constantly and no new moraine material has been deposited. Figs. 5, 6, and 7 shows the extent of the Tyndall Glacier in 1992, 1997, and 2002, during the time it retreated rapidly. This very rapid rate of retreat from 1997 to 2002 (ca. 10 m yr^{-1}) contrasts with the average rate of ca. 3 m yr^{-1} for the period from 1958 to 1997 (Fig.8). Comparing the photos of 1997 (Fig. 9) and 2002 (Fig. 10) illustrates the very rapid recent retreat.

II. Plant Succession in Response to Deglaciation

Fig. 8 shows changes in the position of the glacier front and the leading edge of each advancing plant species (arrow inclination indicates speed of advancement). For example, in 2002, no plants were present within 12 m of the glacier front, and *Senecio keniophytum* and *Arabis alpina* were in areas >12 m away from the glacier front. Moss and lichen were present at distances of 27 m and more.

The first species to colonize new till was *Senecio keniophytum* (Fig. 12b), which advanced at an average rate of 2.7 m yr^{-1} from 1958 to 1984, and 2.1 m yr^{-1} from 1984 to 1992. These rates of advance are similar to the rate of glacial retreat (2.9 m yr^{-1}). Other pioneer species, such as *Arabis alpina*, moss, lichen, and *Agrostis trachyphylla*, advanced at rates between 2.1 m yr^{-1} and 4.6 m yr^{-1} in response to glacial retreat rates of 2.9 m yr^{-1}. *Senecio keniophytum* advanced at 8.8 m yr^{-1} and *Arabis alpina* advanced at 12.2 m yr^{-1}, in response to the

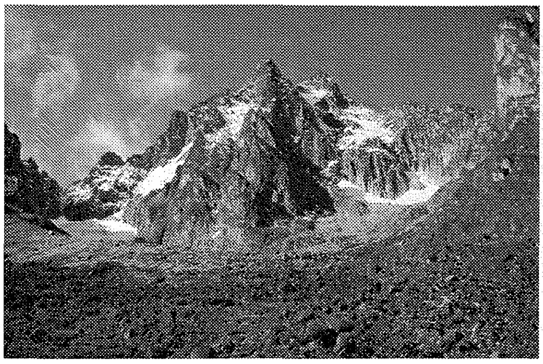

Fig. 2. The summit of Mt. Kenya (5,199 m) and the Tyndall Glacier (left). The upper slope is the Lewis Moraine (white) and the lower slope is Tyndall Moraine I (black).

Fig. 4. Leopard remains discovered on the Tyndall Glacier, Mt. Kenya, in 1997.

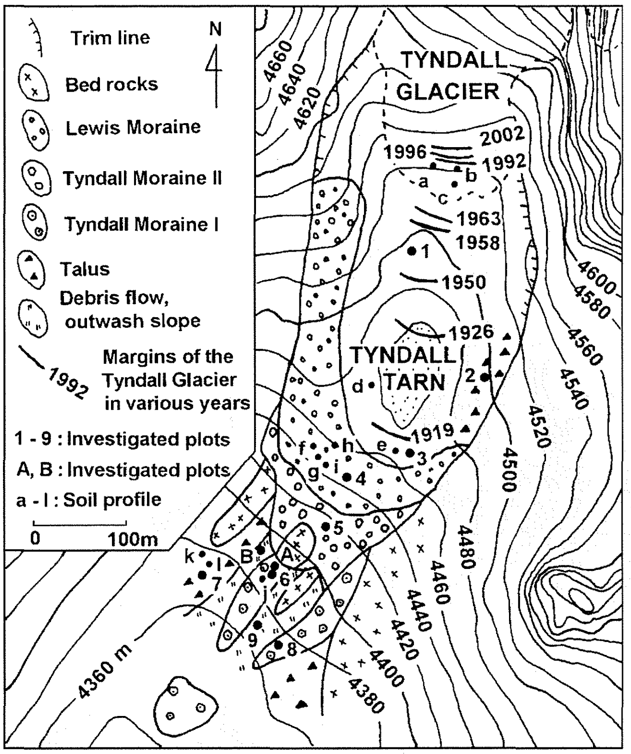

Fig. 3. Geomorphological map for the environs of the Tyndall Glacier, Mt. Kenya. Margins of the Tyndall Glacier for 1919, 1926 and 1963 are from Hastenrath (1983); for 1950 and 1958 from Charnley (1959). Lewis Moraine (Lewis Till) and Tyndall Moraine (Tyndall Till) are from Mahaney (1982, 1989) and Mahaney and Spence (1989).

glacial retreat of 9.8 m yr^{-1} for the interval from 1997 to 2002. *Arabis alpina* eventually got ahead of *Senecio keniophytum*: the leading edge of the area containing *Arabis alpina* was 11.56 m from the glacier front, whereas that of *Senecio keniophytum* was at 11.80 m. Mosses and lichen advanced at a rate of 10.2 m yr^{-1}, and *Agrostis trachyphylla* also advanced at the rapid rate of 6.4 m yr^{-1}. Large woody plants such as *Senecio keniodendron* and *Lobelia telekii*, which did not advance prior to 1997, advanced rapidly at 17.2 m yr^{-1} and

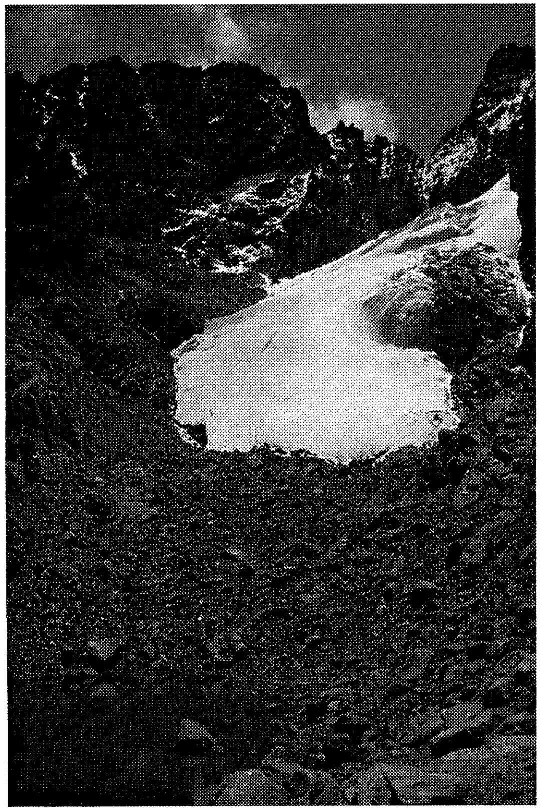

Fig. 5. Tyndall Glacier in 1992.

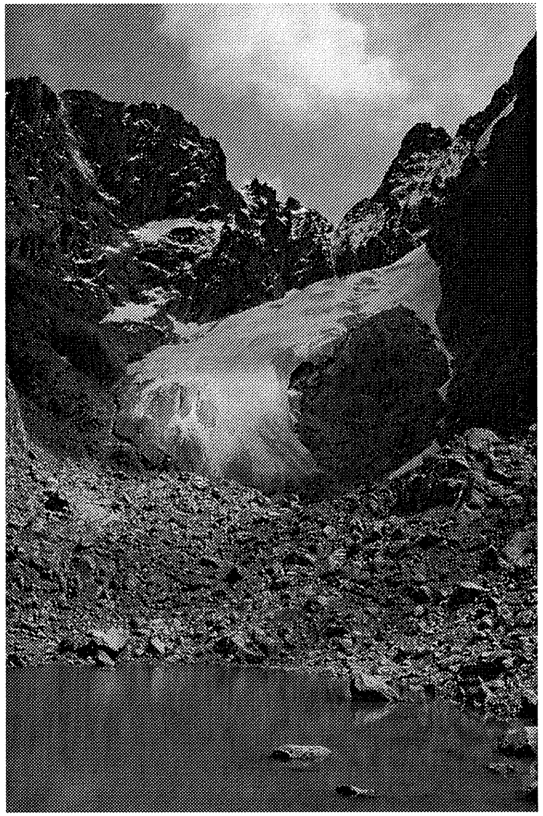

Fig. 6. Tyndall Glacier in 1997.

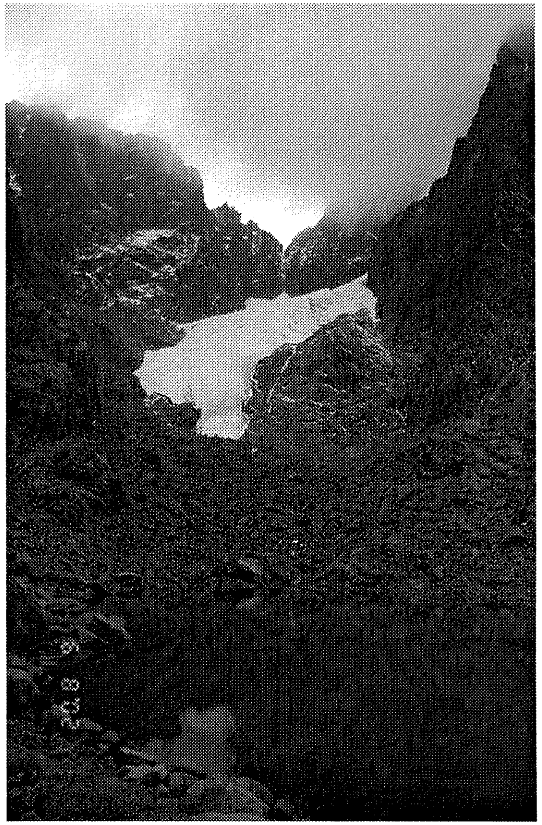

Fig. 7. Tyndall Glacier in 2002.

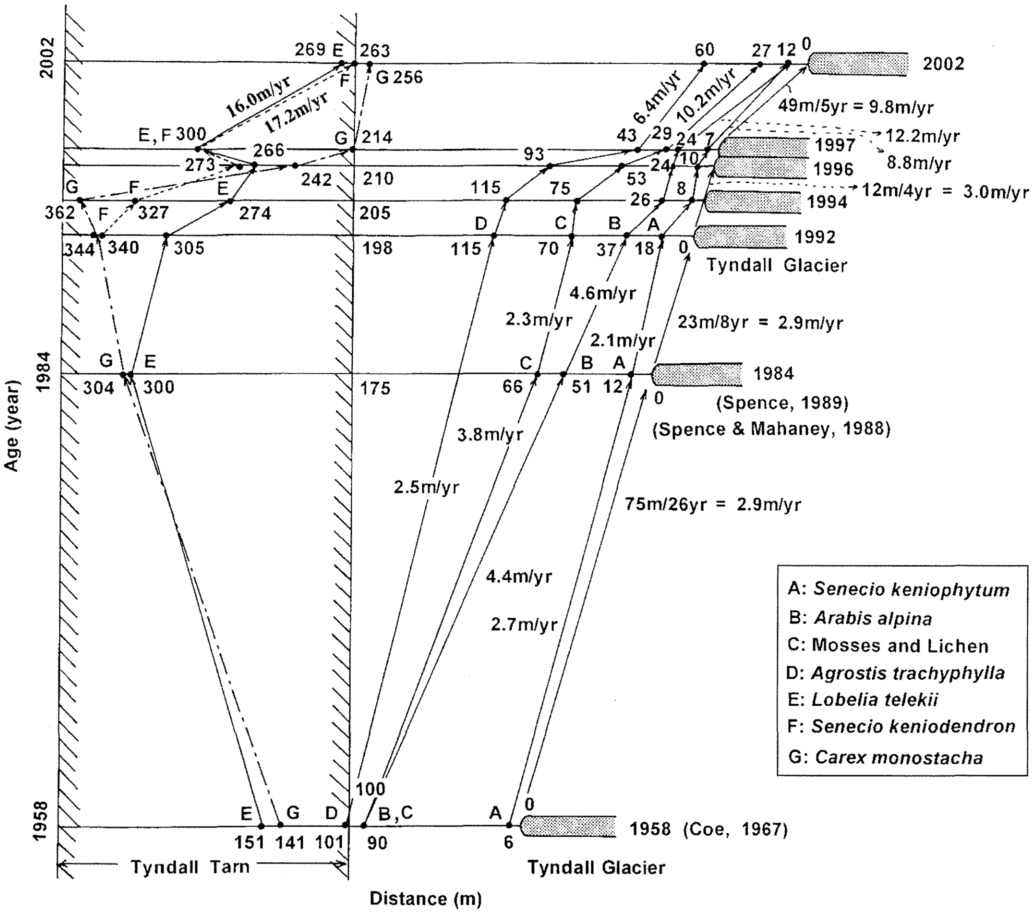

Fig. 8. Glacial fluctuations and succession of alpine plants.
The horizontal axis: distance (m) from the margin of Tyndall Glacier to the front of each plant distribution. The vertical axis: date (the length of the vertical axis indicates years). The arrow: movement of the glacial margin or the front of each plant distribution (the inclination of the arrow indicates speed of movement).

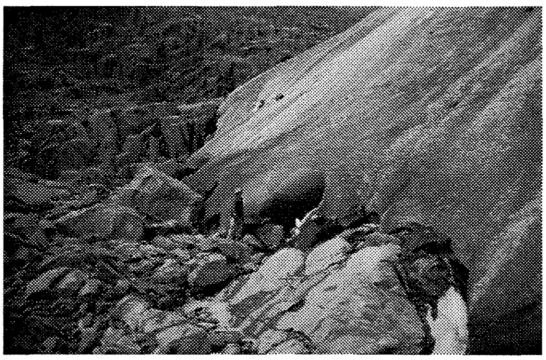

Fig. 9. The front of the Tyndall Glacier in 1997.

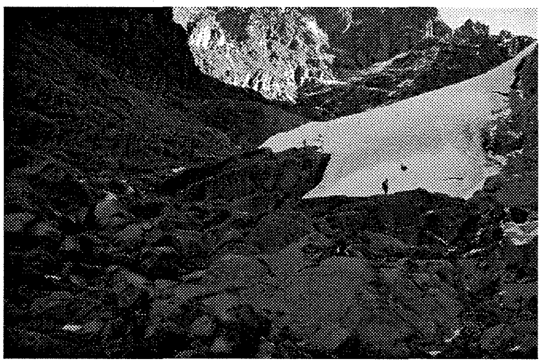

Fig. 10. The front of the Tyndall Glacier in 2002, taken from the same location as Fig. 9.

16.0 m yr^{-1} respectively, from 1997 to 2002.

Near the glacier, the earliest colonizing species, *Senecio keniophytum*, is sparse in the eastern area, which receives less solar radiation owing to the shade of the summit. This species prefers cracks in bedrock on convex slopes such as ridges or banks, because the fine material within the cracks retains water, and the bedrock slope is stable.

III. Plant Succession and Soil Development

Plants change the environments they colonize when they advance into areas formerly covered by glacial ice. Fig. 11 shows the soil profile and till ages (yr) for the study plots, or the time since release from glacial ice. This age, or time, is estimated using the distance between the glacier front and each plot, and the glacial retreat rates [2.9 m yr^{-1} (1958–1992); 3.8 m yr^{-1} (1926–1958)]. For example, the time since release from the glacier ice at Plots a, b, and c (i.e., the till ages) are estimated at 5–13 yr. Soil near the glacier is sandy (loamy sand, sandy loam, and sand) with much fine gravel. Soils are immature, lacking humus content, and thus exhibits dark grayish yellow (2.5Y4/2), grayish olive (5Y4/2), and yellowish gray (2.5Y4/1) colors. In the area closest to the ice-front, only *Senecio keniophytum* grows abundantly. At Plot e, where 79 years have elapsed since glacial release, soil is fine-grained (e.g., silty clay), and its color is brownish-black (7.5YR2/2, 10YR2/2) because of a significant humus content. Soils of this type can support growth of the large woody plant *Senecio keniodendron*.

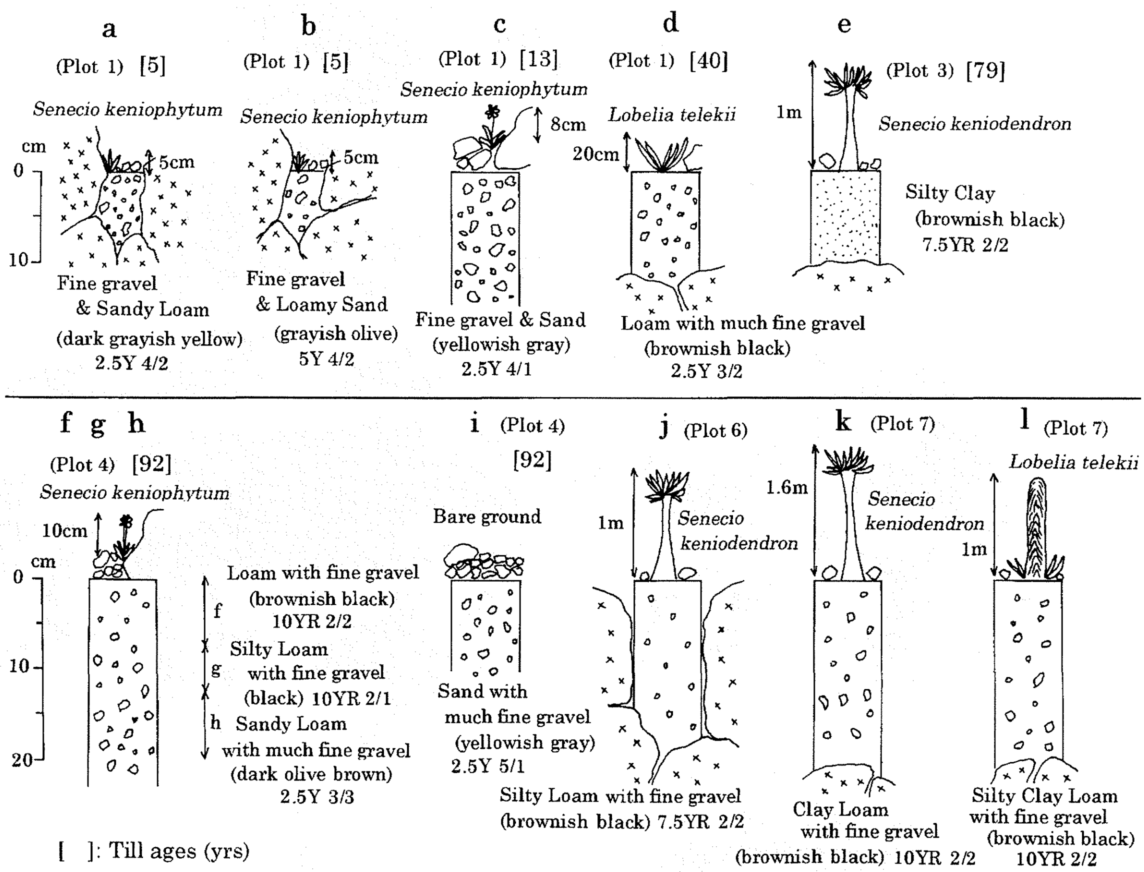

Fig. 11. Soil profiles of plots (Fig. 3). Till ages (yr) of the plots are estimated from glacial retreat rates [2.9 m/yr (1958–1992); 3.8 m/yr (–1958); Charnley, 1959].

Table 1. Environments and composition of alpine plant communities at each plot (Fig. 3) around the Tyndall Glacier.

Plot	1	2	3	4	5	6	7	8	9
Till age (yrs)*	40		79	92					
Landform	Cirque bottom	Talus	Hollow	Lewis Moraine	Tyndall Moraine II	Tyndall Moraine I	Talus	Tyndall Moraine I	Debris flow & outwash slope
Grain-size distribution of surface rubble layer (cm) ( ): Average	1–500 (70)	Debris over fine-grained materials 1–500 (30)	1–300 (50)	Debris over fine-grained materials 1–500 (30)	50–500 (150)	20–300 (100)	1–300 (50)	50–500 (150)	1–200 (30)
Stability of land surface Stable ←——→ Unstable A B C	A	C	A	C**	A	A	A	A	B
Distance from margin of the glacier	Short ←								→ Long
Lichen coverage on exposed block (%)	0	0	30	30	90	95	70	90	40
Vegetation									
Vegetation coverage (%)	1	1	9	2	10	36	45	40	28
Senecio keniophytum	1	1	5	2	8	5		5	2
Arabis alpina	+		1			+			
Tussock Grass (*Agrostis trachyphylla* etc.)	+		+			18	15	14	20
Carex monostachya			+						
Lobelia telekii			1	+	1	3	10	1	1
Senecio keniodendron			1		1	10	20	20	5

* Till ages of the plots are estimated ages based on glacial retreat rates (2.9 m/yr: 1958–1992, 3.8 m/yr: –1958, Charnley, 1959).
** The maximum movement of land surface was 610 cm during two years from 1994 to 1996 and 3,200 cm during 8 years from 1994 to 2002.

Soils capable of supporting the growth of diverse plants develop in environments near the glacier front as a result of improvements made by the roots and humus of pioneer species. Dense growths of *Senecio keniodendron*, *Lobelia telekii* and tussock grass become possible in areas where ice retreat took place ca. 500 yr BP, judging by moraine location and retreat speed of the glacier. At other sites, such as Plot i, few plants were growing in the sandy, yellowish-gray (2.5Y5/1) soil, despite 92 elapsed years since glacial retreat, because of substrate instability (Table 1). The maximum movement of land surface in Lewis Moraine (Plot 4, Plot i) was 610 cm during two years from 1994 to 1996 and 3,200 cm during eight years from 1994 to 2002 (Table 1). The air temperature changed from 0.2°C (8:00 AM) to 5.4°C (3:00 PM) and the soil temperature of bare ground (5 cm in depth) changed from –0.4°C (8:00 AM) to 10.7°C (3:00 PM) at Plot 4 on 5 August, 1994 (Mizuno, 1998). Land surface is unstable due to daily active solifluction from the freeze-thaw. Vegetation coverage is low in Lewis Moraine, because of substrate instability and steep slope. In places with large daily air and soil temperature fluctuations, such as tropical high mountains, daily freeze-thaw cycles cause substrate instability, which strongly influences vegetation distribution.

IV. Habitat of the Large Woody Plants *Senecio keniodendron* and *Lobelia telekii*

Areas where glacial retreat took place a few hundred years ago are generally occupied by large woody plants such as *Senecio keniodendron* and *Lobelia telekii* (Table 1, Fig. 12a). The habitats of *Senecio keniodendron* and *Lobelia telekii* were investigated near Plot 6, where glacial retreat took place ca. 500 years ago. *Senecio keniodendron* and *Lobelia telekii* are particularly present on Tyndall Moraine I and on talus below 4,400 m (Table 1).

The clast size of surficial material and the height of *Senecio keniodendron* and *Lobelia telekii* plants were surveyed at Plot A (4,390 m altitude; Tyndall Moraine I) and Plot B (4,390 m; debris flow and outwash slope) (Fig.3). Large clast sizes are present at Plot A, where about 50% of clasts covering land surface have long-axis diameters of 40 to 70 cm, and over 20% have long-axis

Fig. 12a. Large woody plants of *Senecio keniodendron* (Left) and *Lobelia telekii* (Center).

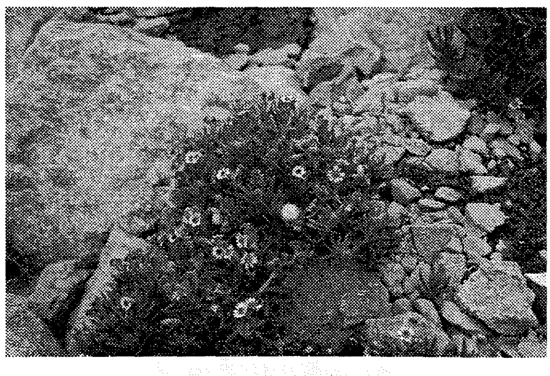

Fig. 12b. Pioneer species of *Senecio keniophytum*.

diameters over 100 cm (Fig. 13a). Smaller clast sizes are prevalent on debris flow and outwash slopes, where debris with long-axis diameters of 10 to 40 cm occupy about 70% of land surface (Fig. 13b).

The population of *Lobelia telekii* is 49 on Tyndall Moraine I (Fig. 14a), and 115 on the debris flow and outwash slope (Fig. 14b). *Lobelia telekii* is generally only 10–20 cm high in August, at both locations, because it dies and regrows mostly every year.

Although the population density of *Senecio keniodendron* is similar at the two sites, plant heights are different. On Tyndall Moraine I, 81% of *Senecio keniodendron* plants are over 50 cm high and 62% are over 100 cm (Fig. 15a). On the debris flow and outwash slope, however, *Senecio keniodendron* plants over 50 cm high form only 22% of the total (Fig. 15b). Although 6 specimens over 50 cm high were present, reflecting long lifespans, the other 21 specimens

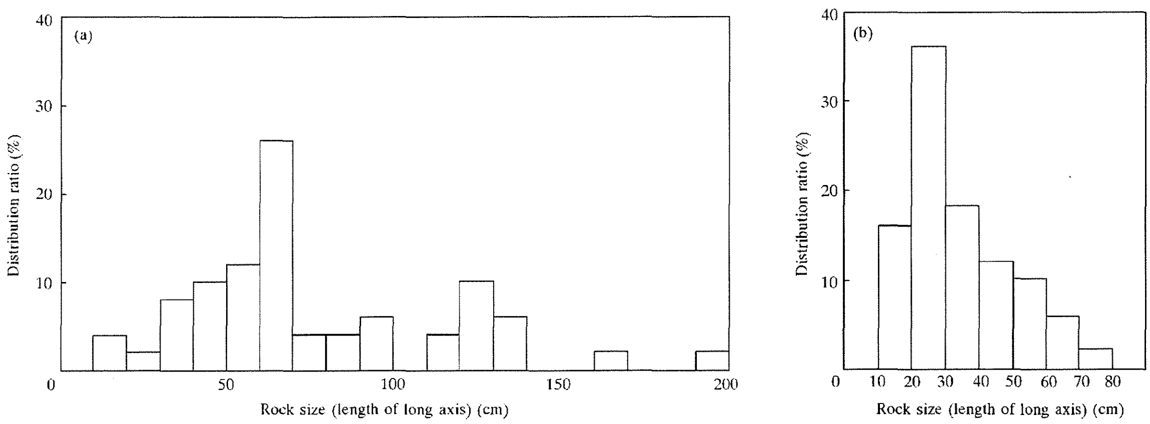

Fig. 13. Debris distribution on (a) Tyndall Moraine I (Plot A) and (b) the debris flow and outwash slope (Plot B).

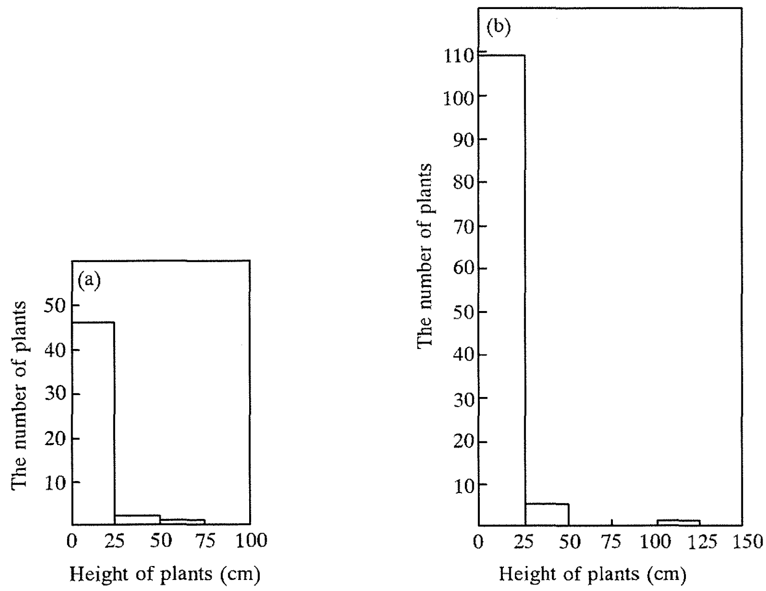

Fig. 14. Height of *Lobelia telekii* on (a) Tyndall Moraine I and (b) the debris flow and outwash slope (August 2002).

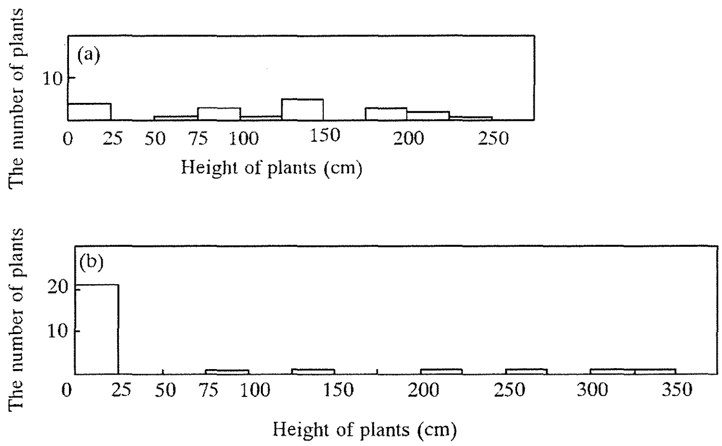

Fig. 15. Height of *Senecio keniodendron* on (a) Tyndall Moraine I and (b) the debris flow and outwash slope (August 2002).

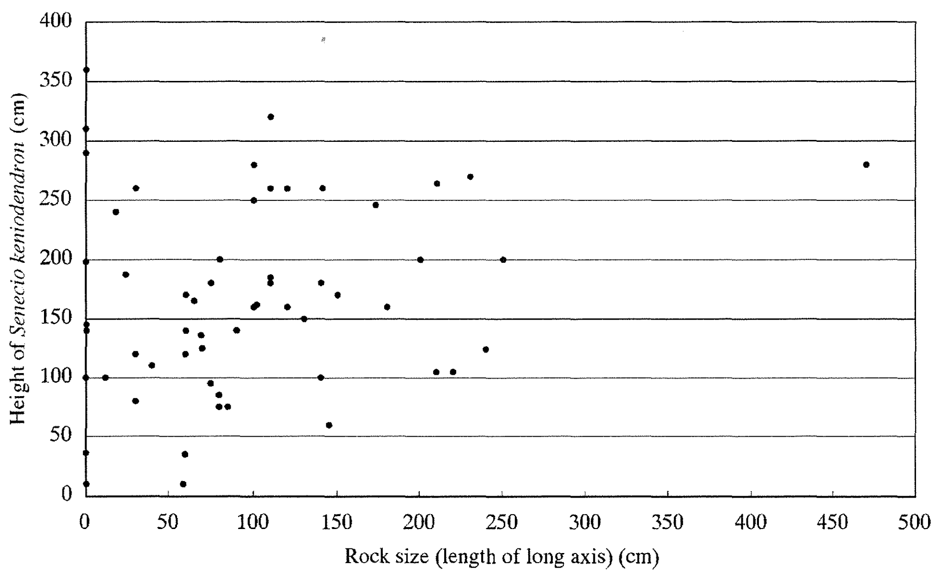

Fig. 16. Relationship between *Senecio keniodendron* height and size of clast long axes in surrounding debris (August 2002). Clast sizes were measured for the biggest debris in ones standing close to *Senecio keniodendron*.

were less than 20 cm high. These latter were new plants that sprouted less than a year before; few of these specimens would survive into ensuing years. As the debris flow and outwash slope site is located in an area of concave topography, plant growth at this site is commonly affected by debris flows or outwash. In contrast, on Tyndall Moraine I the convex topography is not affected by debris flows and outwash, and the substrate is stable, so that *Senecio keniodendron* plants can grow for longer and attain larger sizes. It is interesting to note, however, that the three specimens of *Senecio keniodendron* over 200 cm high at the stable site on Tyndall Moraine I are less than 250 cm high; on the unstable debris flow and outwash slope, however, two of the four specimens over 200 cm high, are actually over 300 cm high. *Senecio keniodendron* height reliably indicates plant age regardless of environment because this plant does not

Fig. 17. *Senecio keniodendron* growing close to large debris clasts.

die and regrow every year. Tyndall Moraine I, characterized by large debris, is a good environment for the growth of *Senecio keniodendron.*

To elucidate this point further, 60 specimens of *Senecio keniodendron* were selected randomly, and the relationship between their heights and the long-axis diameter of the largest debris clasts in the plants' immediate vicinity were measured (Fig. 16). Although the relationship did not emerge as clear-cut, 9 specimens (69%) among the 19 individuals of *Senecio keniodendron* over 250 cm high were associated with debris clasts over 100 cm in diameter. Out of 50 plants over 100 cm high, 34 specimens (72%) were associated with debris over 50 cm in diameter (Fig. 17).

DISCUSSION

I. Deglaciation in the High Mountains of East Africa

The Tyndall Glacier of Mt. Kenya retreated at a rate of ca. 3 m yr^{-1} from 1958 to 1997, but at a higher rate of ca. 10 m yr^{-1} from 1997 to 2002. Recently, acceleration in glacial retreat is prevalent among East African mountains. Fig. 18 shows glaciers on Kilimanjaro in the 1970s (Hastenrath, 1984, 1997) and in 2002 (Mizuno, 2003b). Glacier distribution in the 1970s is based on air photographs taken on 18 March 1972 (Geosurvey Ltd., Peter Gollmer, Nairobi), a photograph taken during a hot-air balloon flight over the Kibo crater on 10 March 1974 (Alan Root, Nairobi), and field observations by Hastenrath in 1971, 1973, and 1974. Glacier distribution in 2002 is based on photographs taken from a light aircraft on 17 August 2002 (Mizuno, 2003b). Glacier extent in 2002 is about half of what it was in the 1970s. This is a dramatic change after only 30 years. The retreat of glaciers on Mount Kenya is well documented for the periods 1899–1963 and 1963–1987 (Hastenrath & Kruss, 1992; Mahaney, 1990). Ice recession between 1899 and 1963 was strongly dependent on solar radiation geometry on any given glacier. In contrast, ice thinning between 1963 and 1987 amounted to about 15 m for all glaciers, regardless of location. This suggests that climatic factors other than solar radiation became more important. The long-term precipitation records for the Kenyan highlands do not support

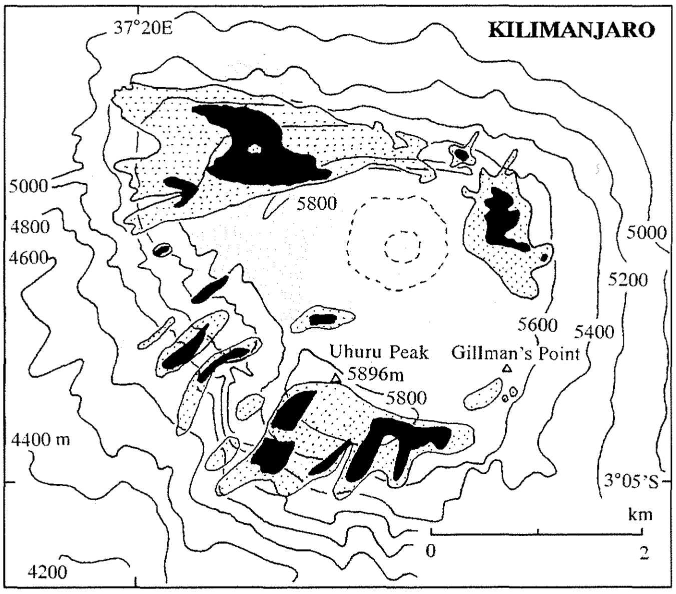

Fig. 18. Glacial cover of Kilimanjaro in the 1970s (stippled; Hastenrath, 1984) and in 2002 (black).

precipitation deficits of such a massive magnitude. Solar radiation/cloud changes, as well as dust/albedo effects, are ruled out by the spatial uniformity of the observed ice thinning. This leaves, as possibly pertinent, the following three heat-budget terms: downward-directed sensible heat transfer from air to ice, which is primarily controlled by the air temperature; upward-directed latent-heat transfer, which is mainly dependent on specific humidity; and net long-wave radiation, which varies mainly with changes in dry-atmospheric composition ("greenhouse effect"), the impact of changing atmospheric moisture being of subordinate importance at the altitude of Mount Kenya (Hastenrath and Kruss, 1992).

II. Vegetation Succession in Response to Deglaciation

All plant species near the glacier advanced as the glacier retreated. The first colonists of new till were *Senecio keniophytum*, *Arabis alpina*, moss, lichen, and *Agrostis trachyphylla.* Their advance rate of 2.1–4.6 m yr^{-1} from 1958 to 1997 was similar to the speed of glacial retreat (2.9 m yr^{-1}). When glacial retreat accelerated to 9.8 m yr^{-1}, from 1997 to 2002, pioneer species advanced at a faster rate: 12.2 m yr^{-1} for *Arabis alpina,* 10.2 m yr^{-1} for moss and lichen, 8.8 m yr^{-1} for *Senecio keniophytum*, and 6.4 m yr^{-1} for *Agrostis trachyphylla. Senecio keniodendron* and *Lobelia telekii* showed no obvious advances before 1997, but advanced rapidly at rates of 16.0 m yr^{-1} and 17.2 m yr^{-1} after 1997.

Rapid glacier retreat generally leads to a succession of vegetation, and causes subtle but serious ecologic changes. Pioneer species improve soil conditions and make the habitat suitable for other plants.

Spence (1989) points out that pioneer succession in front of the Tyndall and Lewis Glaciers proceeds with the appearance first of *Senecio keniophytum*, followed by *Arabis alpine*, and the *Senecio* has fruits with morphological features aiding in wind dispersal and the *Arabis* as well as grasses lack such features. Those species, such as *Senecio keniopytum* and *Arabis alpine*, that can live at nival elevations on the mountain (>4,500 m), appear to be most successful in establishing (Spense, 1989).

Frost soil activity is intense on the till, and as well cold adiabatic winds sweep off the ice surface (Coe, 1967). In particular, when the particle-size of surficial material is small, high water content in the soil causes periglacial processes such as frost-creep and solifluction (Benedict, 1970; Washburn, 1973; Iwata, 1983). These processes, in turn, destabilize the land surface and restrict plant growth (Mizuno, 1998, 2002; Mizuno & Nakamura 1999).

One hundred years after glacial retreat, large woody plants such as *Senecio keniodendron* and *Lobelia telekii* can grow in formerly glacier-covered areas. In such places, the growth of large woody plants is not directly controlled by glacial retreat, but depends on the clast size of the debris covering the land surface and the difference of effect of debris flow and outwash (Table 1). For example, *Senecio keniodendron* can grow in areas of large debris clasts, probably because such substrates are stable. Other benefits of this environment include absorption of heat from sunlight by the debris in the daytime, concentration of water runoff from rock surfaces, and sheltering from wind and snow. Moraines with large clasts are therefore commonly characterized by *Senecio keniodendron*.

CONCLUSION

Atmospheric warming is causing global diminution of glacier cover. Mt. Kenya had 18 glaciers in the early 20th century, some of which have gradually

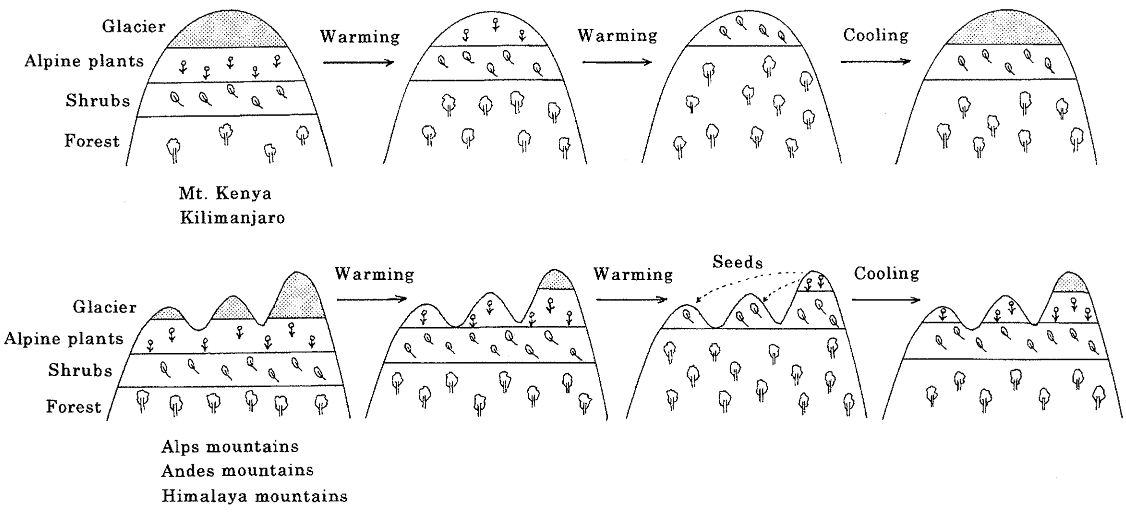

Fig. 19. Theoretical changes in vegetation zones as a result of climate change for an isolated mountain (upper) and for a mountain in a mountain range (lower). If, after an interval of warming, cooler conditions returned to an isolated mountain that caused the eradication of alpine plants, such plants would be unlikely to return. In a mountain belt, however, seed dispersal from one mountain to another would allow recolonization.

disappeared; at present, only 11 glaciers persist (Hastenrath, 1984). When glaciers covering mountain summits melt, plant-cover can expand up the mountains. If warming continues, alpine plant cover may extend all the way to mountain summits, and then eventually diminish as trees colonize the areas formerly occupied by the alpine plants. The Tyndall Glacier has retreated by approx. 300 m in horizontal distance over the 80 years since 1919. In extensive mountain ranges such as the Alps or the Andes, if alpine plants were to be eradicated from a given mountain, they could be replaced by the dispersal of seeds from another mountain. On isolated mountains such as Mt. Kenya or Kilimanjaro, if alpine plants disappear because of warming, it would be difficult for them to regenerate if the climate then cooled (Fig. 19). Ecosystems on high mountains are very sensitive, and apparently even small environmental changes can cause obvious changes in vegetation. Understanding the relationship between alpine vegetation and its environment is critical to tracking global environmental change.

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